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A REVIEW OF ASTRONOMY

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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2006 October 13th at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

M. Rowan-Robinson, *President*
in the Chair

The President. Welcome to the first monthly meeting of the new session. First of all, on behalf of the Society, I'd like to congratulate several people for their awards in the 2006 Birthday Honours list. Firstly, to Professor Carole Jordan of the University of Oxford on being made a Dame of the British Empire for services to physics and astronomy; Professor Andrew Fabian of the Institute of Astronomy, Cambridge, on the award of an OBE for services to science; and Dr. John Butler, research astronomer at Armagh Observatory, on the award of an MBE for services to science. [Applause.]

I want to remind you that the closing date for the RAS–Blackwell Prize and the Michael Penston Astronomy Prize is 2007 January 31. So if you want to find out details of these prizes you should look on the RAS web page, or you can obtain them from the Executive Secretary at Burlington House. I hope very much that you're all using our wonderful new web page regularly. It's updated, there's new information practically every day, and it's a way to keep in touch with what's happening.

Moving on to the refurbishment of Burlington House — next month the Society's apartments will be closed for major works for about twelve months, although we think it will be finished a little before then. The plan is to make this historic listed building fit for the Society's purpose and to be of greater benefit for members, as well as to improve access for the disabled. So we will have wonderful new premises, with a marvellous lecture theatre holding 95 people, refurbished rooms, and a lift. You can read about the planned changes on the RAS website. In the meantime, the regular Friday meetings will continue to be held here in the Geological Society Lecture Theatre and in the Antiquarian Society.

And a final reminder that the 2007 NAM will be from April 16–20, incorporating meetings of the MIST and UK Solar Physics Group, and will be held at the University of Central Lancashire.

Now moving on to the scientific programme, I would like to welcome Dr. Philip Livermore from Leeds, who is going to talk about 'Magnetic-stability analysis for the geodynamo'.

Dr. P. Livermore. By way of introduction, I'd first like to say that I was lucky enough to be awarded the RAS–Blackwell Prize earlier this year, for my thesis work that I will briefly present here today. In summary, I shall address the question of whether the generation of the geomagnetic field can be understood by simple models.

Earth's magnetic field is generated by motions of molten iron in the fluid outer core. The field is, to a first approximation, dipolar and axisymmetric about the rotation axis. This geometry has persisted over the history of the geomagnetic field, and so it is clearly of interest to explain how this configuration comes about, particularly in view of the magnetic fields of other planets (for example, Uranus and Neptune) whose field axes are significantly inclined to their axes of rotation. The geomagnetic field has reversed many times over its history, its current reversal rate being a few times every million years. Palaeomagnetic observations indicate that such events are preceded by a low in the axisymmetric dipolar component of the field, followed by its swift recovery in the new polarity over a timescale of 1000–10 000 yrs. An additional question is therefore how such a rapid growth of the axisymmetric dipolar field comes about.

The geodynamo is driven by convection: flows stretch magnetic-field lines effecting their local amplification, maintaining the field against its natural tendency to decay. However, much like rubber bands, field lines resist being stretched, exerting a force on the flow itself, thereby creating a nonlinear feedback. Although this process is extremely complex, it is possible to simulate the geodynamo on modern computers. However, the parameters used in such models are vastly different from geophysical values, and so despite their success in reproducing fields that are ostensibly Earth-like, the mechanism by which this is achieved may be far from realistic.

So-called kinematic dynamos are a simplification of the fully nonlinear mechanism, in which the force exerted by the field on the flow is ignored. We prescribe geophysically plausible flows (since we don't know what the flow structure is in the outer core) to represent convection, and see whether or not the magnetic fields they are able to generate are similar to the geomagnetic field. To do this, we are required to solve the magnetic-induction equation that describes how the magnetic field changes in time by stretching and diffusion. Historically, it has been attractive to seek exponentially-growing solutions, although despite their successes, there remain two major problems. Firstly, Cowling proved in 1933 that it is impossible to grow indefinitely purely axisymmetric fields; this means that no such growing exponential solutions exist. Secondly, the growth rates are extremely sensitive to the particular choice of flow; since the prescribed flow is poorly constrained, the geophysical realism of any solution obtained is questionable.

The new idea presented in my thesis is that transient growth may be very important. In particular, although it is impossible to grow axisymmetric fields indefinitely, it is straightforward to effect their growth over geophysically relevant timescales by convective motions. I shall consider the possibility of such events as part of the fully nonlinear geodynamo problem, and show that they can give substantial insight into how the dominant structure of the geomagnetic field may be generated.

The problem may be split into two phases: the onset of field growth and its subsequent transient growth. Measuring the strength of the magnetic field by its global energy, we may first compute its maximum initial rate of increase over all fields of unit energy, of all symmetries. This rate will be zero for a critical magnetic Reynolds number, *Rm*, a parameter that measures the strength of the flow. In this solution at onset, for which magnetic fields of axisymmetric dipolar symmetry are preferentially selected, the physical mechanisms involved can be easily understood by field-line stretching near the 'rotation axis', where the poloidal flows are vertically divergent. In cases with and without an inner core, this process is the same despite significant differences in the structure of the flow pattern.

Transient growth may be characterized by the maximum amplification of magnetic energy taken over all initial fields of unit energy. Again, fields of axisymmetric dipolar symmetry are favoured for convective flows, and the mechanism of growth is similar to the onset problem: field is advected towards the 'rotation axis' and then vertically stretched. Amplification by a factor of around 1000 is possible for geophysically realistic values of *Rm*, and indeed the timescales over which such growth occurs is of the order of 1000 yrs, geophysically relevant for both the geodynamo mechanism itself but also consistent with the recovery time of such a field component after reversals.

In summary, I have discussed how the kinematic dynamo problem can shed light on the highly complex and fully nonlinear geodynamo. Treated firstly as part of the fully nonlinear mechanism, transient growth goes some way to explaining how the geodynamo is able to generate a field that is predominantly axisymmetric and dipolar, although we require an additional unspecified process to maintain the field in between these events to allow the dynamo to operate indefinitely. Secondly, the rapid growth associated with the transient mechanism I have described could also explain how the field recovers after the intensity low preceding magnetic reversals.

The President. I apologize for not mentioning that Dr. Livermore is a recent RAS–Blackwell prize winner. There's plenty of time for questions.

Dr. N. Kollerstrom. The geomagnetic-field vector has quite large diurnal fluctuations in both magnitude and direction, and also has quite a marked monthly periodicity due to the 27-day solar plasma acting on the Earth. Does your model take account of these at all?

Dr. Livermore. You're talking about the external field coming from the Sun?

Dr. Kollerstrom. The geomagnetic field as measured at the surface.

Dr. Livermore. Oh, I see. No, we're talking really just about the internal geomagnetic field, nothing to do with the external solar wind.

Professor P. G. Murdin. You mentioned in your introductory remarks that the Earth contrasted with Uranus and Neptune, so what's the Earth got that these don't have?

Dr. Livermore. Perhaps I shouldn't have mentioned this. [Laughter.] I'm by no means an expert on other planetary dynamos, and I don't think very much is known about the internal structure of Uranus and Neptune. The short answer is, I don't know.

Professor N. O. Weiss. If I can follow up on that, sticking of course to proper planets. Doesn't Mercury lack an inner core? Does that affect its magnetic field?

Dr. Livermore. Well, one of the good points of this analysis is that the physical process by which the magnetic field is generated is not dependent on whether there's an inner core or not. We rely solely on the fact that there's convection. So, in theory, any planet with a convecting core, could exhibit this kind of process.

Professor Weiss. Could the field be sustained indefinitely?

Dr. Livermore. Possibly, yes. This mechanism relies on something else, because one cannot indefinitely maintain a dominant axisymmetric field. You need some other ingredient which is not specified here.

Professor D. J. Southwood. I don't want to advertise, but for the moment Saturn has an aligned dipole field, as far as everybody knows, and if you wait for a few minutes you'll learn something else. But the planets can be rather irritating for dynamo theory. It violates the Cowling theorem.

Mr. M. F. Osmaston. The rate of reversal has increased since the Cretaceous period. This seems to me to indicate that the rate of reversal is being controlled by a slow variation of some parameter. Do you have a feel for what that parameter might be?

Dr. Livermore. Well, that's a very difficult question to answer. No. As I indicated on one of my earlier slides, there's been a lot of work on numerical simulations and how many of these have exhibited reversals. Not many have exhibited multiple reversals. They simply can't integrate for long enough in time to have a feel for the kind of long-term processes that you're asking about.

Professor I. W. Roxburgh. I wanted to comment to David Southwood that you shouldn't take Cowling's theorem as too much of a constraint. With non-axisymmetric motion you can get an almost axisymmetric field in principle. I don't know the mechanism for it.

Professor R. Hide. I was interested in Mr. Osmaston's question about superchrons. Although the average interval between polarity reversals of the main geomagnetic field is about a million years, over the past 400 million years there have been two superchrons each lasting as long as about 30 million years. The first of these occurred during the Permian, when the field polarity was opposite to its present sense, and the second during the Cretaceous, when the polarity was the same as it is now. One leading palaeomagnetic worker expressed the view that whatever the mechanism that produces reversals might be, someone kept it switched off during superchrons! Intermittent slow convection in the Earth's mantle gives rise to lateral changes on geological timescales in the boundary conditions imposed on core motions. Geophysicists seem to accept that Coriolis forces render core motions particularly sensitive to such changes. And there are reasons for expecting non-reversing dynamos under the simplest imaginable boundary conditions.

The President. I think that sounds like a very firm way to end this discussion. Thank you for your talk. [Applause.] The next talk is 'Education and outreach with an 1860 Cooke 10-inch refractor' to be given by Charles Barclay.

Mr. C. E. Barclay. As a relatively new member of the Society, I am very pleased to have the opportunity to present and highlight the work which is centred on top of the Marlborough Downs in Wiltshire and which is now being mirrored in Oxford.

I shall focus on education and outreach rather than the history of the telescope, which I presented to the Society for the History of Astronomy (SHA) at their annual conference last year. A paper is also about to be published in the SHA magazine, *The Antiquarian Astronomer*.

I should start by declaring myself to be a teacher first and foremost, having taught physics for 16 years and astronomy GCSE for ten, so my job is educational rather than research based. My background is in astronomy having taken a degree in Astronomy and Astrophysics at St. Andrews University culminating in an Honours thesis on extreme helium stars under Dr. Phil Hill. I arrived at Marlborough College, a leading independent co-educational boarding school as Head of Physics some 41 years after the 1860 *Barclay* 10-inch Cooke telescope was sited there and opened in a purpose-built observatory by Harold Knox Shaw, the last Radcliffe Observer in Oxford. (The coincidence of the provenance of the telescope, having been made for my great-grandfather's first cousin Joseph Barclay, who was elected to this Society in 1855, was not discovered until 2001.)

Oxford Radcliffe Observatory had used the 10-inch for 50 years, covering research into double stars, comets, and planets. It distinguished itself above other UK instruments by recording the most extensive light curve of the 1885 supernova in M31, but encroaching Oxford enforced the Observatory's move to South Africa in 1935.

At Marlborough from 1935 onwards, the telescope had been used in an ebb and flow of enthusiasm by pupils and teachers. Until the outbreak of war in 1939, many papers were written internally, though not officially published, and covered such aspects as variable stars, sunspots, timings of the orbits of Titan and the Galilean moons, and the partial solar eclipses of the late 1930s.

This degree of interest and activity never returned after the war and by 1997 the telescope was largely neglected and non-operational, the worm-wheel drive being beyond repair.

Funded by the College, we embarked on a full restoration project and employed ex-Herstmonceux astronomer Norman Walker, now working independently in the design and supply of dome and telescope equipment to professional institutions and amateurs. As well as restoration we decided to modernize whilst keeping to original materials, and using a purpose-designed tensioned-belt-drive system, we computerized both axes. (My research so far leads me to believe this is the oldest telescope in the world to have a 'GO TO' function.) [Laughter.]

By 2002 the telescope was being used again and the Blackett Observatory was reopened by Joe Silk, Savilian Professor, reflecting the Oxford connection.

The telescope when built was one of the largest to come out of the new Cooke works at Buckingham, and indeed ranked as one of the largest refractors in the UK. It was immediately obvious that the restored telescope had huge potential both as an inspirational piece of engineering and as a first-class working telescope with superb optics.

Astronomy is now in a golden era; media coverage and initiatives from scientific groups including this Society are at an all-time high. I am pleased to see the most recent front cover of *A&G*, featuring an article by Francisco Diego on outreach at UCL's Mill Hill Observatory. Educating the next generation is vital, but can, of course, be done by books or computers. What is most needed is inspiration. It is the hands-on experience of observing, staying up later than parents or school rules might allow or seeing a projected image of the Sun up close, that captures the imagination. Once inspired, internal motivation will drive the will to learn and will generate interest and allow decisions to be made which buck the trend of contemporaries opting for 'softer' subject options. In my opinion this needs to occur before year 9 (*i.e.*, age 13–14 years).

Ties between the Blackett Observatory and Oxford were strengthened further when I took on a Public-Understanding-of-Science link rôle within the Oxford Astrophysics Department as an Academic Visitor. In 2004, together with Roger Davies, I applied for a PPARC Small Award to get young people to real telescopes, to fund outreach at the Blackett Observatory and at the newly re-sited *Philip Wetton Telescope* (*PWT*) in Oxford, hence allowing graduates to take part in local school outreach and to put together a programme of lectures and visits.

We are delighted that the Award has been renewed this year and this has enabled us to host more than 1000 visitors and reach out to some 1500 *via* lectures last year.

With the increasing significance of the 10-inch Cooke and its potential within Marlborough College, I was appointed the first Director, transferring from my post as Head of Physics in 2004.

The educational use at the Blackett Observatory falls into two categories: (*i*) GCSE Astronomy, which has been taught since 1997 with numbers rising from six year-11 pupils then to 55 from years 10 and 11 this year. All 165 pupils in their first year are introduced to the observatory in one-hour evening sessions. There is also access for local schools and colleges (including adult-education groups) who offer the GCSE course, to make use of the facilities. (*ii*) Outreach started in 2004 and involves public evenings and afternoons (a prime initiative was to equip the 10-inch with both broadband and Hα solar filters, which has increased observational time by well over 100%). Local primary-school and preparatory-school visits are arranged both for teachers and pupils and, though space restricts numbers to 20 at any one time, up to four repeat sessions are sometimes necessary. We now also have links to the Science Museum at Wroughton, just south of Swindon, and will combine with the museum for events such as the evening of the close approach of Mars last October, for which we had a stream of visitors.

Marlborough has also been a centre since 2003 for the NASA Sun–Earth-day lecture initiative, raising public awareness of the Sun–Earth connection.

In Oxford, we are planning a link with the new Islamic centre (Oxford Centre for Islamic Studies) and hope to combine this with an exhibition of Islamic high-precision instruments to include astrolabes from the Oxford Museum of the History of Science, but already groups are visiting the *PWT* from local schools, youth groups, and as part of a week's visit of sixth formers funded by the Sutton Trust.

With grants from the Heritage Lottery Fund, Green College in Oxford, on the site of the old Radcliffe Observatory, have started holding public open days to raise awareness of the historical importance of the old observatory. We had some 700 visitors one Sunday last month and I lectured throughout the afternoon on the astronomy which had been carried out there. Last May, through the Green College–Oxford Astrophysics–Marlborough link, we instigated a series of three PUS lectures given by myself, Roger Davies, and Jocelyn Bell-Burnell, all free and each with full audiences of 100 visitors. Hopefully the lecture series will be an annual event.

With Dr. Rene Rutten, Director of the ING on La Palma, I have been able to set up a link whereby school pupils can 'piggyback' on allocated university research time and spend two nights on the *INT*. Though the groups are small, being briefed and then involved in front-line research and its follow-up has been inspirational, and two of the pupils have already gone on to read maths and natural sciences at Oxford and Cambridge. The first year we worked with an Oxford group and last year with a researcher from the Kapteyn Institute. For the present, the pupils have to be self-funded and this has been a limitation, but I am hopeful that funding can be sought, given the educational value of secondary/tertiary links and the cross-European nature of the visit. Holland already has a well-funded system allowing schools to access the already set-aside educational time on the *INT* and submit their own observational proposals. I am aware that the futures of the *JKT* and *INT* are under discussion but hope that educational use of a significant telescope in a superb site with inspirational value for school students can be maintained.

I have long been a proponent of astronomy in education. Falling numbers in science (especially physics) are well documented. Astronomy is bucking this trend and its GCSE exam, unlike others at this level, maintains rigour and depth of knowledge. Media coverage and publicity reach all school children and the enthusiasm of ten- and eleven-year olds is infectious; question-and-answer sessions always have to be curtailed. Yet by age 13, this has gone, science is 'uncool', and scientists are 'boffins' (as school-level media representation continually insists). I am very fortunate having an observatory under single-person control, no time-allocation problems, minimal budget complications, and easy access, but most of all the superb optics. Though the observatory is equipped with a variety of CCD cameras, so far the demand for 'eye-to-eyepiece' observing has been overpowering. The remote-telescope projects such as the 'Telescope in Schools'/*Liverpool Telescope* and *Las Cumbres/Faulkes Telescope* projects have been so well publicized and funded that they have made a significant step forward in widening access and bringing telescopes into the classroom and teaching. What we are doing on a local scale, as at Mill Hill and Greenwich, is to provide the inspirational experience of large telescopes.

At the end of the day pupils can see remote telescopes as another computer project, with images that can be manipulated. I believe it is the experience of witnessed events, for example, the Apollo programme and manned spaceflight, a rocket launch, eclipses, Comet Hale-Bopp, and the Leonid storms, that are the 'hooks' rather than images or data acquisition. Seeing something for oneself is a totally different experience and it is the 'wow' moments that make the long hours worthwhile. The motivation and inspiration of real time 'in the cold' observation must not be underestimated or lost, and thus the drive for strict regulations regarding light pollution are paramount, as is the importance of early, year-7/8 exposure at schools if excitement is to be maintained.

In summing up, I would like to think that a Victorian telescope, which was briefly at the forefront of research in a time of UK engineering dominance of the Industrial Revolution, can inspire, even on a local scale, children of a UK which has for some time been suffering scientific educational decline at secondary-school level. It is easy to become immersed and focussed on front-line astronomical research, but if successive generations are not enthused in this country, this room may be an emptier place in 30 years' time. [Applause.]

The President. Well, thank you for that very inspiring talk, and Fellows who have been reading *Astronomy & Geophysics* attentively will know that I've been urging the RAS to embark in various directions, but one of them definitely is to expand our education and outreach activity. I think this is a superb example of the kind of thing the RAS needs to be supporting. If your own university or institution is not doing something like this, it's time to think about it. So I'd like to open the floor for questions.

Dr. R. Massey. Thanks, Charles, and you know I certainly endorse the work you're doing, because I know what we've done in Greenwich with public access to the telescope is very effective. I don't know what came of things a few years ago to better relations between the independent and state school sectors, but how many pupils a year do you get through from adjacent secondary schools? Are you contacting them and bringing them in as well?

Mr. Barclay. Bringing them to the telescope, absolutely, yes. We have nine primary schools within a very small area and they're all queueing up to come. I can take one, and then they want to come back. So actually, it's almost impossible. But yes, they're all very much coming in. However, as the telescope is owned by the College and because I teach there, the prime use has to be internal. GCSE Astronomy numbers at the College were six when I started up in 1997 and we now have 55 people doing this subject. It's a pretty major thing to get them through the coursework, but, as far as the outreach goes, it's entirely state schools' and teachers and pupils.

Dr. Massey. Do you get secondary schools in as well?

Mr. Barclay. Not yet, although we have been in contact with them. I'm also trying to be as broad as possible. We've had a couple of visits from astronomical societies as well, but that has not been my aim initially. I don't want to say that they can't come, but in a sense I don't want to preach to the converted. I should have said, of course, that Greenwich as well as Mill Hill is doing fantastic work. I only mentioned Mill Hill because it was in the *A&G*.

Mr. P. D. Hingley. Thank you very much for your kind comment, and congratulations on your excellent talk and work. If anyone actually wants to know about the history of the *Barclay* telescope, by joining the Society for the History of Astronomy now you'll be just in time to receive the third issue of *The Antiquarian Astronomer* — and Mr. Barclay's excellent article — which I shall be posting just before Christmas.

The President. Any other questions?

Dr. D. McNally. Could I ask you a very specific question about that telescope? Cooke telescopes of that period sometimes have a very nice additional extra, where you only have to set the hour angle once per night, then you just dial up the right ascension. Does your telescope have that?

Mr. Barclay. Yes. It certainly is one of the first that was produced in the new Cooke Buckingham works in 1860. It's also one of the largest, and I think when it appeared it was among the top four to six largest refractors in the UK. Although quickly superseded it was produced to a very high specification. Joseph Barclay was obviously very determined to have a nice telescope.

Dr. McNally. This is why they've lasted so well and are virtually student proof to this day.

Mr. Barclay. Yes, certainly. The optics are absolutely superb, and I think if it hadn't have been the original lens I wouldn't have felt quite the same. Last night I had a pupil who was mapping 100 or so stars on the outer edges of M13. The resolution is just amazing. The professional astronomers who have come and used it, and the graduates from Oxford, all are fairly astounded at the resolution we can get. On the Sun, for example, we can see Hα prominences with very fine detail.

Dr. G. Q. G. Stanley. If you catch people early, you catch them in perpetuity, as you seem to be following on from your great grandfather's cousin. Will you be forming any links with things like the *Faulkes Telescope, etc.*?

Mr. Barclay. The *Faulkes Telescope* project and the *Liverpool Telescope* project are outreaching into schools in vast numbers and that is fantastic. You can use them in the classroom and it captivates people in a very different sort of way. We have looked at the projects and I have been to the training days. The pupils often see the computer project as just another computer project, but because we have this facility, getting people to the eyepiece and maybe staying up a bit later than either parents or schools approve, and actually seeing with their own eyes, is really the thing that captivates. I'm so busy doing that, and during the day with physics; but yes, it would be very useful to participate in those projects.

The President. It might be worth drawing the attention of Fellows to the fact that 2009 has been declared the International Year of Astronomy, and the IAU and UNESCO are both supporting this. One of the goals of that year is to get everybody in the world to look through a telescope, ideally, but not necessarily, at the moons of Jupiter to commemorate the 400th anniversary of Galileo's discovery. So this is something to think about, for a project in 2009. There's plenty of time to organize some vast public event to allow people to look through a telescope. Thank you very much again for your very inspiring talk. [Applause.]

Dr. McNally. Are you going to turn the lights of London out for half an hour?

The President. We're working on it!

The President. The next speaker is Simon Jeffery from Armagh. The title of his talk is 'Pulsations in subluminous B stars: a question of opacity'.

Dr. C. S. Jeffery. If my title seems somewhat obscure, then it only serves to provide a framework for this evening's presentation. I hope to demonstrate, in turn, just what the subluminous B stars are, and what makes them interesting, the nature of their pulsations, and why opacity is so important for their interpretation.

For orientation, I remind you of the typical colour–magnitude (or Hertzsprung–Russell) diagram for a globular cluster, which shows the main sequence, a giant branch, and an horizontal branch. This horizontal branch is composed of evolved stars now burning helium in a core of about 0·5 solar masses, overlaid by a hydrogen-rich envelope. Moving blueward, we encounter stars with decreasing envelope masses until, in theory, we reach the helium main-sequence. The first evidence for such stars was obtained from surveys of faint blue stars in the galactic halo. These demonstrated a substantial number of B and O stars between the main-sequence and the white-dwarf cooling track — evidently on an extension of the horizontal branch. These stars have shown up in all surveys of faint blue stars, outnumbering quasars in the Palomar-Green survey by factors of twenty or more. They have been found in globular clusters and, hence, have come to be known as extreme- or extended-horizontal-branch stars. They have also been shown to be responsible for the ultraviolet excess observed in giant elliptical galaxies. Thus, subdwarf B or sdB stars are ubiquitous in highly evolved stellar communities.

The question of their origin presents a challenge: single-star evolution theory cannot produce such a star. Interaction with a binary companion is necessary to remove the hydrogen-rich envelope from the progenitor red giant. The fact that Nature can make these stars in at least four ways is all the more intriguing, but one we have no time to explore today.

It is the pulsations of sdB stars that concern us. The EC14026 variables were discovered some ten years ago by Kilkenny and co-workers at the SAAO. They were predicted by Charpinet and co-workers in Montreal at about the same time. These stars show multiperiodic oscillations with periods between 60 and 600 seconds. Some 35 are now known, and substantial effort has been made to resolve their pulsation frequencies and to use these for asteroseismology. Three years ago, a second group of variable sdB stars were discovered by Green and co-workers. These PG1716 stars have multiple periods in the 30–120 minute range. The question for both groups is what drives the pulsations.

There has been pioneering work on this question by, variously, Charpinet, Fontaine, Kawaler and co-workers. To cut a long story short, EC14026 pulsations are closely related to β Cepheid pulsations, in a way analogous to the connection between classical Cepheid and RR Lyraes. High opacities due to M-shell electrons in iron-group elements were discovered in the early 1990s by the OP and OPAL projects. This opacity bump ('iron-bump') at a temperature of $\sim 2 \times 10^5$ K is responsible for β Cepheid pulsations. EC14026 variables lie in the same temperature domain, and are unstable to low-order radial and non-radial pulsations (p-modes) — but only if the abundance of iron in the driving zone has been elevated by a substantial factor.

PG1716 variables are cooler than EC14026 variables; two stars lie on the boundary at around 29 000 K and exhibit the properties of both. They are likely to be g-mode pulsators. Fontaine *et al.* showed that such modes are unstable in extended horizontal-branch stars, but only for effective temperatures below 25 000 K and, again, only if the driving-zone iron abundance has been elevated.

Thus several puzzles remain. Roughly one half of stars in the PG1716 domain appear to be variable — and thus should have an elevated iron abundance. Therefore, why is only one in ten stars in the EC14026 instability strip variable? Why is the theoretical blue-edge for g-modes too cool? And how can a star acquire such high overabundances of iron?

The last question is, perhaps, the easiest. The radiative envelopes of sdB stars are very calm environments where the strongest forces acting on an atom are gravitational and radiative. While the accelerations due to gravity are the same for all ions, the radiative accelerations are not. Over time, different elements will diffuse to bring these accelerations into equilibrium, so that high chemical concentrations may be found in regions of high specific opacity.

Hideyuki Saio (Tohoku University, Sendai) and I set out to understand and, if possible, answer the other two questions. We show first the distribution of variable sdB stars as a function of effective temperature and luminosity. The results of our stability analysis are then overlaid, showing the stability boundary and contours of increasing instability — the number of unstable modes. We computed such boundaries first as functions of hydrogen abundance (X) and metallicity (Z). Instability is obtained by increasing the contrast between the Fe-bump, either by reducing X or by increasing Z. The first refers to the case for extreme helium stars, the second to sdB stars. However, even at very high Z (20% by mass), we see that the blue edge is too cool. Saio and I realized that we could tailor the opacity tables to consider only iron as the varying component of the metal contribution. As we see, this shifts the instability strip to higher temperature, matching the locus of EC14026 stars with an iron over-abundance ~ 10. A similar property is found for g-mode pulsations. In fact we identified a small region of instability for unmodified abundances. However, like Fontaine, we could not obtain instability for any models hotter than about 25 000 K.

After concluding a paper summarizing these general results, Saio and I wondered what we could do to make the g-mode blue edge hotter. We recalled the well-known result that the temperature of an instability strip is related to the temperature at which an opacity peak occurs. Although the 'iron-bump' is generally considered to be dominated by iron — iron is at least ten times more abundant than other nearby elements — we wondered whether any other element might contribute opacity at a higher temperature. On investigation, we found that nickel contributes opacity at a temperature slightly higher than iron, and does it very efficiently despite its low abundance. However, when we tried to include nickel in our stability analysis, we found no difference.

It turned out that, by chance, we had made the nickel/iron comparison using OP opacities, while we had done the stability analysis with OPAL opacities. The OP data have been revised in recent years to include many more transitions than before. Looking more carefully, we find that, in OP, both iron and nickel currently contribute more opacity and at higher temperature than in OPAL. When we use OP opacities, and include nickel, we discovered that the g-mode blue edge shifts to ~ 28 000 K, much closer to the observed blue edge of the PG1716 variables.

With this knowledge, we recently returned to look at the radial (or p-) modes. We have just found that, by including nickel and using OP opacities, the p-mode blue edge is also shifted strongly to the blue. As a consequence, we can match the observed location of EC14026 stars by assuming far lower overabundances than with OPAL. This will have significant consequences for our understanding of the EC14026 variables. It is clear that understanding pulsations in subluminous B stars really is a question of opacity.

What has been satisfactory about this work is that it points to solutions of quite hard problems that are relatively easy to understand. Simply by including elements that had been neglected for convenience, and by adopting improved atomic physics, we have found significant changes in the stability results that lead to much closer agreement with observation. Moreover, the results have provided an observational test of the atomic-physics calculations which was entirely unexpected, but a vindication of the effort that went into making them.

Fellows may examine the results in recent publications of the Society (*MNRAS*, **371**, 659, 2006; *MNRAS*, **372**, L48, 2006; and *MNRAS*, in preparation). I am grateful to PPARC for the travel and visitor funds that have enabled this collaboration with Saio, and I hope that the title of my talk is now less opaque than when I began.

The President. So, any questions? Ian?

Professor Roxburgh. Are the stars in general very slowly rotating? Or if not, could there not be interference with settling from circulation currents by rotation?

Dr. Jeffery. They're not rotating fast, they're not like young B stars. The rotation periods for those that we have tried to measure have been of the order of a few days. On the other hand, a number are in relatively short-period binaries. Whether all of those pulsate or not is not clear. There is a clear problem because only one in ten sdB stars pulsates in a region where we would expect either all or none to pulsate. So rotation might be a way that we can separate those that pulsate from those that don't.

Dr. P. F. Chen. For these stars are the p-modes and the g-modes strongly coupled?

Dr. Jeffery. Not normally. Most of them only pulsate in one mode or the other, or one set of modes or the other. There are two objects which pulsate with both g- and p-modes, both long and short periods. To see whether there is a coupling between them or not is going to take a lot of observational effort.

The President. OK, let's thank Dr. Jeffery again. [Applause.]

The President. Our next speaker is Professor David Southwood. He used to be my Head of Department at Imperial, but he decided that that particular bed of nails wasn't sharp enough, and he went off to become Director of Science at ESA. He is going to talk about 'Saturn's magnetic rotation: an update and an explanation'.

Professor D. J. Southwood. The rotation period and the magnetism of Saturn have been vexed topics for many years. Initial reports from *Pioneer* and *Voyager* spacecraft fly-bys more than twenty years ago reported that the internal magnetic field of Saturn appeared to be axially symmetric and equivalent to a dipole that was shifted slightly from the planet's centre along the rotation axis — the magnetic measurements thus yielding no evidence of any off-axial internal field component. The absence of a clear non-aligned component of the dipole at Saturn appeared a quandary for dynamo theory as it violates a basic tenet, Cowling's theorem.

The discovery of a periodically varying kilometric-band radio signal (SKR) was thought to have resolved the paradox. It was assumed that the modulation detected in the SKR was due to a high-order magnetic anomaly in the auroral zone, undetectable in the equatorial regions. However, the extended coverage of SKR radiation offered by the very sensitive *Ulysses* spacecraft radio instrument and subsequently confirmed by the *Cassini* spacecraft showed a regular drift of order 1% per year in the period. This seemed unlikely for an internally generated field and threw the issue once more into doubt.

More puzzles emerged. In a re-analysis of the *Voyager* and *Pioneer* data a few years prior to the *Cassini* arrival at Saturn, the Imperial College group found a signal in the magnetic field at the radio period. Mysteriously, the polarization made it clear that the source was external to the planet and unlike any magnetic signal of planetary origin reported elsewhere in the Solar System. A simple mechanical model, the 'camshaft' model, was proposed to explain the manner in which the variations were generated near the planet and then propagated through the system.

Cassini's two years in orbit have shown more clearly that the external periodic magnetic signals are a permanent feature of the system at this epoch. A first analysis of the periodicity using data near periapsis (between 3 and 15 R_S (Saturn radii)) for the first 15 months in orbit led to identification of a magnetic period of $647 \cdot 1 \pm 0 \cdot 67$ min. The uncertainty almost precisely matched the range through which the period of the SKR evolved in the same time. One could conclude that the two signals had the same fundamental origin. Field-aligned current systems are a natural explanation to link both phenomena. However, the magnetic polarization contributed the surprising fact that the currents seem to flow from hemisphere to hemisphere rather than being driven by ionospheric–magnetospheric coupling.

The Fourier technique for the initial magnetic-period analysis used the Lomb–Scargle algorithm for extrapolating phase between periapsis passes, which does not lend itself to identifying a slowly varying period. Accordingly, recent work has used phase mapping of individual peaks following a superposed epoch analysis. This technique does allow tracking of a varying period and present results of work still under way confirm that the rate of change of period for SKR and magnetic field is not distinguishable. However, there are off-sets in period at any particular time with the shorter period being detected by the magnetometer. Grouping data by radial distance ($< 8R_S$, 8–12 R_S) the magnetometer signal seems to shows evidence that the period offset may vary with radial distance but remains below the SKR period.

In this work we propose a mechanism which can resolve many of the observational and theoretical problems. Could there be a transverse dipole shielded in some way at distances ($< 3R_S$) where *Cassini* has rarely been? It is shown how electromagnetic induction in a massive conducting ring embedded in tenuous magnetospheric plasma could both shield a rotating dipole and generate a cam-like exterior signal. Moreover, might the shielding process throw light on the slow period variation? If the electrical conductivity of any of the massive material in the vicinity of the A, B, F, or G rings is light-sensitive, it would seem possible. A preliminary re-analysis of the only data received where *Cassini* penetrated inside the B-ring inner radius ($< 1 \cdot 59 R_S$) (during orbit insertion) suggests that this cannot be ruled out. Furthermore, should the speculations here bear fruit, there are new avenues to be explored concerning other phenomena having their seat in an electromagnetic effect of rings and their electromagnetic properties.

When the 'camshaft' model was proposed, it was assumed that the field displacement would be north–south symmetric. In fact, the *Cassini* data have made clear that what has been identified as the basic magnetic signal is associated with ionosphere-to-ionosphere field-aligned current and so the displacement is antisymmetric about the equator. Nonetheless, once the interaction between the signal imposed by the rings and the region beyond where the mass-loading of ionized material from Enceladus and the E ring is allowed for, the rotation of the dipolar field region of Saturn's magnetosphere does impose an asymmetric force like a mechanical cam on the outer system. *Cassini* has shown that the asymmetry is a basic feature of the system and the rotating structure is imposed to very great distances (many tens of R_S) in Saturn's vicinity.

Several colleagues deserve credit for useful discussions and advice in analysis and interpretation of the data: M. K. Dougherty, S. Kellock, of Imperial College, London; M. G. Kivelson, K. K. Khurana, UCLA; A. Lecacheux, Observatoire de Paris, Meudon, France; V. M. Vasyliunas, MPI für Sonnensystemphysik, Lindau, Germany. It is particularly pleasant to acknowledge publicly S. Kellock's part in building with me the *Cassini* spacecraft fluxgate magnetometer from which the data used in this study have come. [Applause.]

The President. Questions?

Dr. Chen. Are there any similar phenomena for Jupiter?

Professor Southwood. Well, Jupiter's rings are much less substantial, and I actually think we have to go back to the Jupiter data to take a look, because frankly I don't think anyone has thought about it. I don't see why it shouldn't be there but if you think about current in the ring, and it looks like it's there in magnetometer data, we need to go back and carefully check the calibration of the data and get the size of the asymmetric dipole identified. So far we have not been calibrating allowing for the effects I have talked about here being present. Another issue is the planet's shadow. If the conductivity is photo-sensitive on the night side, you might get a sort of capacitance. Of course, the edge of the shadow is where the spokes appear — they are also connected to the rings' electrical state.

Professor Hide. What a fascinating story! In the much simpler case of Jupiter, from what radio astronomers tell us the radio period has for several decades been disappointingly constant and very close to the rotation period of longitude System III based on the radio-period, namely 9 hours 55 minutes 29·711 seconds. This is fairly close to the rotation period of the extra-tropical regions of the cloudy atmosphere (and as much as 5 minutes greater than that of atmospheric tropical regions), but it must reflect the motion of lines of magnetic force tied to electrically-conducting material underlying the atmosphere. There is some consistency between Jupiter and Saturn if the same general interpretation applies to the 10 hours 47 minutes radio period for Saturn. This is much closer to the rotation period of extra-tropical atmospheric clouds than it is to that of tropical clouds, which is as much as twenty minutes shorter.

Professor Southwood. There is a cornucopia of issues to clarify even if I'm only half right. I don't think that the differential rotation can tie in with zonal flow in the atmosphere. It seems more likely to originate in the (internal) field itself. Moreover, I don't see why the time evolution of the differential atmospheric flow would be synchronized at different latitudes. You have also to start thinking about the seasonal effect of the solar incidence angle, because of course we're in the middle of the southern winter of Saturn now. When the period was shorter, I suspect we had the rings much more edge on, when there might have been a smaller electromagnetic effect. But that's speculation — please don't go and bet the house on that.

The President. I don't think William Hill would take a bet on that! [Laughter.] Any other questions?

Dr. A. N. Fazakerley. Is there any kind of auroral emission other than the kilometric radiation that you put forth?

Professor Southwood. There's a lot of auroral radiation at Saturn. At times it's quite exciting. At other times it's disappointingly less exciting than the magnetosphere looks to be from the *in-situ* measurements. There is my own prejudice in that, but of course what you do see on Saturn are things that look like rotating sub-storms, with the sort of break-up type behaviour that you see at Earth, but rotating around the planet. I think you're seeing that the whole planetary plasma environment is basically structured by such periodic behaviour.

The President. Thank you very much. [Applause.]

The President. Before I close the meeting, we've got a couple of minutes. I wish to take a rather frivolous vote. Some of us were at the IAU this summer, and we found ourselves obliged to vote on your behalf on the nature of planets. [Laughter.] I feel that we should consult the membership to see whether we reached the right decision. Now, this vote has absolutely no significance, it is purely for...

Professor Roxburgh. It'll be in the papers tomorrow... [Laughter.]

The President. ...it is purely for interest. So the issue, as I'm sure you're aware, is that definitely defined major planets — classical planets — are planets which are dynamically dominant, of which there are eight, and then there are dwarf planets. The decision of the IAU is that dwarf planets are not planets, so I wish to put this to you: Should dwarf planets be planets or not? You have planets, and you have 'dwarf planets', with a quote around them.

A Fellow. So, can you define dwarf planets for us?

The President. No. [Laughter.] You get that from television.

A Fellow. Is there a size below which....

The President. Goodness me, it's been in all the newspapers and television, so you should be up to speed on this. If you don't know what I'm talking about then don't vote. [Laughter.] Assuming we all know and have an opinion, I just want to know what your opinion is.

Dr. A. Chapman. To be politically correct, shouldn't they surely be called 'vertically challenged' planets? [Laughter.]

The President. Those in favour of the IAU point of view that dwarf planets are not planets... OK, thank you. Those who favour the view that dwarf planets are planets... Right, there was a majority for the first option.

Professor Roxburgh. Anybody change their mind? [Laughter.]

The President. So, it was about two to one here, and at the IAU General Assembly it was about three to one. So it looks as if those present got it roughly right, at least reflecting the majority of those here; but you're just as divided if not slightly more divided.

A Fellow. How many people abstained?

The President. Oh, I'm not interested in that. [Laughter.] There will be the usual drinks party over in the Society's apartments at Burlington House, to which you're all very warmly welcome. The cost is one pound per head. This is your last chance to see the apartments in their present form. In a year's time they will emerge, like a butterfly from a chrysalis, in a completely new form. During this year, we will not be able to have a drinks party in Burlington House and we have not come up with any alternative so far.

Dr. McNally. Does this mean we have to clear the cellar tonight? [Laughter.]

The President. I didn't know there was a cellar. So anyway, please come to the drinks party. The next open meeting will be held on Friday, 2006 November 10.

ORBITS OF HYADES MULTIPLE-LINED SPECTROSCOPIC BINARIES

PAPER 5: THE QUADRUPLE SYSTEM HD 30869 (VAN BUEREN 124)

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HD 30869 (van Bueren 124) is a bright (6^m) F-type star which, though in Orion, has long been regarded as a well-attested member of the Hyades. Already in the 19th Century it was discovered to be an unequal visual binary, and after a time it became clear that the orbital period is about 100 years. Fifty years ago suspicions arose that the radial velocity was variable on a relatively short time-scale, and in the 1980s two syndicates independently published spectroscopic results that showed the visual primary to be an unequal double-lined binary with an eccentric orbit having a period of about 143 days; at the more favourable node of the orbit the system was seen as triple-lined. What impels us to discuss the system afresh now is the discovery, made from high-resolution spectra taken at the McDonald Observatory, that the visual secondary, too, is a spectroscopic binary; we demonstrate that it is double-lined and has an eccentric orbit with a period just short of 500 days. On many occasions (mostly selected, however, to be near the more-favourable node in the spectroscopic orbit of the visual primary) it has been possible to see all four sets of lines separately in the spectrum and to measure good velocities for them all. We are also able to estimate the spectral types of the three faint stars and to provide a photometric model of the complete system.

A discussion of the radial-velocity results in the context of the visual orbit leads to the conclusion that the latter is now unassailable, and certain discrepancies between it and some of the earlier radial velocities must be attributed to errors in the velocities. In our discussion of the two spectroscopic orbits, therefore, the progressive changes that motion in the long-period orbit causes in the γ-velocities is accounted for on the basis of the visual elements in preference to being solved for from the radial velocities themselves.

Introduction

HD[1] 30869 (van Bueren[2] 124, ADS[3] 3483, HIP[4] 22607) is a sixth-magnitude star in the north-preceding corner of Orion, one-third of the way from Aldebaran (α Tauri) towards Bellatrix (γ Orionis). In recent editions (only) of *Norton's Star Atlas*[5], it is shown as a dot with a line through it (indicating duplicity); it is about 1° preceding the fourth-magnitude star labelled o^2 Ori, the northernmost tolerably bright star in Orion's shield. It is most unlucky not to possess a number in the *Bright Star Catalogue*[6], since with a V magnitude 6·27[7] (we note here also the colour indices[7] $(B-V) = 0^m{\cdot}497$, $(U-B) = 0^m{\cdot}059$) it is well above the nominal threshold of $6^m{\cdot}5$ that qualifies it for inclusion; its misfortune stems from the $6^m{\cdot}70$ that was accorded to it by the visual photometry of Pickering & Wendell[8], which was unusually inaccurate by its own standards and led to the omission of the star from the 1908 *Revised Harvard Photometry* volume[9] which subsequently served as the source list for the *Bright Star Catalogue*. The original visual photometry[8] was listed afresh, together with that for many other stars found to be fainter than the cut-off for the *Revised Harvard Photometry*, in a companion volume[10] published in the same year as that work. The modern magnitude is in fact given in the current *Bright Star Catalogue*[6], but only in Appendix III at the back of the book, where it is included in a listing of about 200 stars that had come to attention by that time (1982) as being brighter than $6^m{\cdot}5$ and yet lacking a *Bright Star* number. It was only natural, therefore, that it *did* appear in the *Supplement to the Bright Star Catalogue*[11] that was brought out in the following year. The Appendix-III list includes 18 stars which had been assigned magnitudes even brighter than that of HD 30869, but associated notes indicate that, even at that time, a few of them were already considered to be actual or probable mistakes; our own private review now shows that only ten of them are genuinely brighter than HD 30869.

There is a rich and extensive observational history behind HD 30869; salient aspects of it were related in a paper[12] in which one of the present authors collaborated some 20 years ago, so it is only briefly summarized here. Among the topics for which the interested reader is referred to the earlier paper are photometry, spectral-type and luminosity estimates, and the evidence for HD 30869 being a member of the Hyades star cluster.

It was in 1877 that the remarkable double-star observer S. W. Burnham[13] first definitely saw HD 30869 as a visual double star, with a separation that he gave as "$0''{\cdot}8\pm$" and that has proved to be quite uncharacteristically inaccurate, and with a magnitude difference of 3^m, when he observed it with the 18½-inch Dearborn refractor; later, however, he noticed[14] from his observing books that he had suspected its duplicity three years earlier in an observation made with his own 6-inch. He[13] assigned it his 'discovery number' β 552; it appears in his great double-star catalogue[14] of 1906 as BDS 2383 and in Aitken's subsequent one[3] as ADS 3483. Of course, at the time that Burnham was observing it, most of the now-familiar catalogue designations were unavailable because the catalogues concerned did not then exist; probably the only designation that would still be recognized as being in common use would be the *BD* one[15] of +13° 728. Long before the publication of the *BD* in the mid-19th Century, however, diligent astrometrists had been at work compiling catalogues, and at first sight it is intriguing that in one of them — the posthumously published (1847) one by Baily[16] of the re-reduction of Lalande's observations made about fifty years earlier — *two* stars, Lalande 9109 and 9110, are listed at the expected (epoch 1800) position of HD 30869. They are noted as having magnitudes of 6½ and 7, and are about four seconds of arc apart. But other stars in Baily have double (in some cases multiple) entries too, and the explanation is to be found in the *Preface* (p. viii), which clearly states, "When stars have been observed more than once, each result has been set down as a separate star."

Within 20 years of Burnham's discovery, the system had shown 180° of orbital motion. Unfortunately it had not been re-observed for most of that time, and it soon became apparent that a periastron passage had been missed. All the same, orbital solutions began to be published, to prove not to represent the continuing measurements satisfactorily, and to be superseded. To our knowledge, twelve successive orbits have been published; we refrain from giving references to them all, but refer readers to the ninth of them, by Scardia[17], for a listing of the elements and references for all the previous ones. We note, however, that Scardia's reference to 'Baize 1954' would preferably be to *Journal des Observateurs*, **36**, 155, 1953, and also that the diagram of the orbit in Scardia's paper has an erroneous scale bar — the numbers on it should be doubled. Subsequent orbits have been given by Heintz[18], Starikova[19], and most recently (post-*Hipparcos*) by Söderhjelm[20]. That last one had the advantage of being able to draw on observations covering a large arc around a new periastron passage that occurred about 1982, and to include many accurate measurements made by speckle interferometry. All the same, it does not represent the continuing observations as well as they *can* be represented, and we feel called upon to substitute our own solution below.

The total mass of a binary system is obtainable simply from the semi-major axis of the orbit and the period, through the expression $\Sigma m = a^3/P^2$, where m, a, and P are all in Solar System units of solar masses, AU, and years, respectively. For visual binaries, a is not determined directly in linear terms but in angular measure, so a knowledge of distance (or, equivalently, parallax) is needed to give the mass sum. Because the parallax enters the expression cubed, like the orbital radius, and has historically not been measurable with much relative precision at the distance of the Hyades, mass sums proposed for HD 30869 have varied wildly. Thus, at one time Eggen[21,22] considered the sum of the masses to be only $1 \cdot 34\ M_\odot$, whereas on another occasion[23] he gave it as $4 \cdot 05\ M_\odot$. Heintz[18] put the total mass at $2 \cdot 2\ M_\odot$, and remarked that "[the] data seem to indicate that the primary is undermassive ...". Scardia[17] noted that the possible mass sum ran from $2 \cdot 33$ to as much as $7 \cdot 5\ M_\odot$, depending upon what source one adopted for the parallax, prompting the cynical comment in our earlier paper[12], "so we are, perhaps, at liberty to select a total mass that does not conflict with other parameters of the system". The value most recently proposed, by Söderhjelm[20] in the light not only of his own new orbital solution but also of the *Hipparcos* parallax, is $3 \cdot 11\ M_\odot$, for which he estimated an uncertainty of 14%.

For nearly fifty years the only radial velocities that had been measured for HD 30869 were the three published in 1914 by Adams & Kohlschütter[24] from the Mount Wilson Observatory. Our earlier paper[12] recounts how, between 1961 and 1981, a succession of authors made modest numbers of radial-velocity observations of the system and tended to find variability greater than could be ascribed to motion in the visual orbit, prompting repeated suggestions that the system is of higher multiplicity. Heintz[25], in particular, in 1981 identified the visual primary as being "evidently" a spectroscopic binary. In a brief paragraph in the 1980 annual report of the David Dunlap Observatory[26] (DDO) Turner & Lyons were mentioned as having discovered that HD 30869 is a spectroscopic binary and as making systematic observations of it to determine its orbit. In the corresponding report[27] the following year, the period of 143·5 days is noted. The DDO work came to fruition in 1986, when Turner & Lyons, in collaboration also with Bolton, published[28] in this *Magazine* an orbit based upon 35 photographic spectrograms, all but one of which were taken with the DDO 74-inch reflector, mostly at a dispersion of 12 Å mm^{-1}; they began in 1973, and had stopped already in 1980.

Although, by the time of the DDO publication[28], no fewer than six authors or syndicates (the details absent here are all to be found in our earlier paper[12]) had described their suspicion or certainty of the triple nature of HD 30869, not one of them had referred to the presence (or for that matter the absence) of evidence in the spectrum for the existence of the two stars other than the one whose velocity they had measured. Even if the visual primary, whose more luminous component must be the star in the 143-day orbit, were single-lined, *i.e.*, if its *spectroscopic* companion were unobservably faint, its spectrum ought still to exhibit some admixture with that of the visual secondary. The magnitude difference, Δm, of the visual pair has been accurately determined by *Hipparcos* to be $2^m{\cdot}01 \pm 0^m{\cdot}02$. Previously, Δm values judged by visual observers had ranged between 1^m and 3^m, and the discussion by Baize[29] had led to a best estimate of $1^m{\cdot}61$ (again, references will be found in the previous paper[12]). Thus the visual secondary must necessarily contribute something like $^1/_6$ as much light as the primary to the combined spectrum. Owing to the nature of the 143-day orbit, which has a high eccentricity (0·6), the velocity of the primary remains for most of the orbital period quite close to the γ-velocity, and the ease of detecting other contributors is not helped by the fact that its spectral lines are smeared out by a considerable rotational velocity, which had been put by Kraft[30] at 25 km s^{-1}. At the node that is reached shortly before periastron passage, however, the primary exhibits a velocity minimum that takes it (slightly) more than 25 km s^{-1} away from the γ-velocity.

Shortly before the HD 30869 spectroscopic orbit was published from the DDO, it had been derived (as one of 16 orbits for Hyades-area stars) in the paper[12] already mentioned. In that paper, one of the present authors had collaborated in bringing to bear, for the first time on HD 30869, the cross-correlation method[31] of determining radial velocities. There were 52 measurements, giving the period and the form of the orbit, that were made with the prototype photoelectric spectrometer[31] at Cambridge; the star was difficult to measure with that instrument, because it gave dips that were so shallow and wide, and it was noticed that they became still worse — still more diffuse, and asymmetrical — during the brief minima of velocity. Much more informative regarding the actual profile of the 'dip' in the trace were the 16 observations obtained with the spectrometer constructed by Griffin & Gunn[32] at the coudé focus of the 200-inch Palomar telescope. By good fortune one particular Palomar observing run coincided with a nodal passage of HD 30869, when the primary was at its minimum velocity; a radial-velocity trace was obtained then with a very high S/N ratio, and is illustrated in the paper[12] (Fig. 22). It shows a beautiful profile, albeit having a depth of only 6% of the 'continuum' and broadened by a projected rotational velocity quantified at 22·5 km s^{-1}, for the star that we shall call Aa, the primary in both the visual binary and its spectroscopic sub-system. Blended into the red wing of that wide dip there is a long shoulder that clearly consists of at least two additional components. The redmost end of it was confidently attributed to the secondary star, Ab, in the visual primary, since traces at other phases showed no component near that velocity, and that part of the profile was well matched by that of a star about two magnitudes fainter than Aa and having negligible rotational velocity. We can do no better than to quote directly what was said[12] about the remainder of the profile, an infilling murky blend that had to represent the visual secondary, B, between the parts assigned to Aa and Ab:

> "The part of the dip that is not accounted for by Aa and Ab is quite well matched by a rotationally broadened profile for B. Instead of rotational broadening, twin unbroadened components could be postulated. There is at present [no]* clear observational basis to permit an informed choice to be made between the alternatives. In the discussion that follows, we assume that B is a single star. That hypothesis leads to a reasonably self-consistent model of the system; but if in the future it is proved to be erroneous, then the total mass and (to a greater extent) the mass ratio of the visual components will require revision, as will some other aspects of the discussion."

The major incentive for the present paper is to announce the discovery that B is in fact itself a double star. We are, however, already able to go a lot further than merely announcing the discovery, by giving double-lined orbits for both visual components and offering a comprehensive quantitative model for the whole quadruple system.

Before presenting our new observations and a fresh discussion of the HD 30869 system, we can usefully recapitulate how matters stood with regard to the visual and spectroscopic orbits twenty years or so ago, after the publication of the two orbits (by Griffin *et al.*[12] and by Turner, Lyons & Bolton[28]) for the short-period binary that constitutes the visual primary star. Both those orbits were already recognized at the time to be very rough, because they were based almost entirely on radial-velocity measurements that treated the whole system as if it were a single star, having a single radial velocity, which was attributed solely to the component we are calling Aa. A direct comparison is made between the elements of the two published orbits in Table II of Turner *et al.*[28]; the similarity of the two is in many ways surprisingly good, but we remark here upon the differences in (*a*) the r.m.s. residuals, 1·4 and 2·3 km s^{-1} for refs. 28 and 12, respectively, and (*b*) the periods, 143·53 ± 0·05 and 143·27 ± 0·06 days, respectively.

The apparently worse residuals found by Griffin *et al.*[12] arise partly from the weighting convention, described in Section II of that paper, whereby observations made with the 200-inch telescope were attributed weight 4, those made with the original spectrometer at Cambridge being given unit weight. Thus, if the weighting were indeed realistic, the actual Palomar residuals were only half as great as the listed r.m.s. value, which was specifically noted as corresponding to unit weight. In any case, it could be expected that the longer time-span covered by the Palomar/Cambridge measurements in comparison with those made at the DDO provided more opportunity for the un-modelled variation of the γ-velocity arising from motion in the ~ 100-year visual orbit to contribute to the apparent raggedness of the velocities. Indeed, the downward drift of the velocities was noticeable enough to draw specific comment in the paper[12].

The period discrepancy of 0·26 days, whose formal standard error, compounded from those of the separate orbits, is only 0·08 days, need not be taken too seriously: it arises principally from the interaction of the progressive slippage of the γ-velocity with the exact distribution in the 143-day orbit of the phases of observation. Turner *et al.*, who as authors of the later orbit were the only ones who were in a position to comment on the comparison, mildly remarked that there were indications that the true period lay between the two values. They actually gave a reference to the earlier paper[12] at the very word "indications". Regrettably the relevant passage is none too easy to follow, and we take this opportunity to clarify it. The orbital solution in the paper concerned[12] was based solely upon the

*Regrettably the word 'no' is missing from the original publication[12] owing to an error on the part of the publishers. In the proof, there was a defect in the type in that word, and it was so marked by the authors, but what the publishers did was to delete the word altogether instead of substituting unblemished type.

Palomar and Cambridge measures that were being newly presented, although all previously published radial velocities of which the authors of that paper were aware were listed in the journal of observations and plotted in the diagram of the orbit. It was noted that the solution resulted, "at first sight rather pleasingly", in placing three very low velocities, reported[33] as having been measured at Mount Wilson in 1910, at almost exactly the correct phases to minimize their residuals. Unfortunately, it also led to two velocities published in 1965 by Kraft[30], one from the Mount Wilson coudé and one from the Palomar one, appearing at impossible phases, at which they had residuals of 31 and 16 km s^{-1}; "to bring them to a phase that is even remotely tolerable requires ... an increase of period to 143·5 days" — and then, of course, it was the 1910 Mount Wilson measures that would fall at altogether the wrong phases. The authors[12] felt it incumbent on them to express their choice between those measures and Kraft's, and "unhesitatingly" chose Kraft's.

On the face of it there is a contradiction between, on the one hand, that forthright choice, and on the other, the orbital solution that was actually published, which fits the 1910 observations but not Kraft's. The adopted solution, however, did not set out to fit *either* of those sources but was based only upon its authors' own observations, and the ensuing discussion was concerned only with how well it represented velocities from other, previously published, series. When that is appreciated, the implication is clear that the 1985 authors considered that the true period of HD 30869 A would need to be increased from the value found from their own data to at least 143·5 days — which in retrospect would bring it close to the the DDO value[28] of 143·53 days. The reason that they refrained from including Kraft's velocities in the orbital solution, or presenting a solution upon which the appropriate period was imposed, was that Kraft's observations were made at an epoch well outside the span of all the others, were consequently affected to a very substantial but unquantifiable extent by motion in the visual orbit, and were, after all, themselves blends of at least three components: it seemed out of proportion to base the whole solution upon an estimate of their phasing, although it was very clear that the period of the adopted solution was unsatisfactory as it stood. We shall show below that the true orbital period of the primary sub-system, at 143·59 days, is actually higher than was proposed either by Turner *et al.*[28] (whose estimate must have been biassed in the same way and for the same reason as Griffin *et al.*'s[12], but not so much, owing to the shorter time base) or by Griffin *et al.* as being the minimum needed to bring Kraft's observations to a "tolerable" phase.

Radial velocities — needs and difficulties

After the 1985 orbit paper[12] was written, the author (R.F.G.) whom that paper has in common with *this* one felt an interest and indeed responsibility to continue observations in an effort to provide solutions to the substantial problems that remained outstanding. One of those problems related to the effect on radial velocities of the motion in the ~100-year orbit, in which at the time of writing of the earlier paper the system was just about at periastron; another was the nature and radial velocity of the visual secondary, B, which according to a very preliminary discussion had been at a velocity 10 km s^{-1} removed from the expected one on the only occasion when it had appeared to have been measured with any confidence.

Owing to the impossibility of disentangling, *i.e.,* obtaining reliable radial velocities for every component independently from, traces in which the dips of all the components were superimposed, there seemed to be little purpose in observing at times other than those of the nodal passages that occur near periastron. Such passages occur only once, or sometimes twice, per observing season, so the opportunities are quite restricted. A further misfortune was the observer's loss after 1986 of the use of the 200-inch telescope, which was the only one to which he had access that was capable of giving traces (such as the one in Fig. 22 of the published paper[12]) that would be fully satisfactory for the purpose even at the node. The original spectrometer[31] at Cambridge, which was still in operation until 1991, offered only a very limited S/N ratio; the Dominion Astrophysical Observatory spectrometer[34] had a complex and idiosyncratic instrumental profile which created extra difficulties and uncertainties in unscrambling traces exhibiting multiple dips; while the OHP and ESO *Coravel*s[35] had maximum scan ranges that were not wide enough to include the whole dip profile of HD 30869 at the node, and the observer had no access to the traces once they had been obtained and so could not experiment with them. All that it seemed possible to achieve in practice was the measurement of the velocity of the principal component, Aa, when it was near to the node at which its velocity was a minimum. Much later, when the Cambridge *Coravel* became available, it promised some progress on other aspects of the task, but was overtaken by the extraordinary success of the campaign begun independently by J.T. at McDonald Observatory, as we describe below.

At this point it seems appropriate to interpolate some disparaging remarks concerning radial-velocity spectrometers that incorporate physical masks, as did the original one[31] and several of its successors[32,34,35]. It has long been appreciated, *e.g.,* ref. 36, that the larger the telescope the greater the difficulty in designing an efficient spectrograph for it. For that reason, the instrumental profile of the radial-velocity spectrometer that was set up[32] on the 200-inch telescope was somewhat wider than the profiles obtained at the smaller telescopes, the basic reason being the difference in image scale and thus of the typical linear (as opposed to angular) size of the star image at any given focal ratio. Moreover, for reasons of luminous efficiency the mask in a radial-velocity spectrometer has to transmit more than an infinitesimal proportion of the total light in the spectrum, so the transparent gaps that correspond to absorption lines in the stellar spectrum must not be made very narrow. In fact, detailed numerical modelling convinced the successive makers of the Cambridge[31], Palomar[32], and Haute-Provence[35] spectrometers that for optimum performance of the instrument as a whole the widths of gaps in the mask needed to be approximately equal to the typical widths of absorption lines in the spectra that were to be imaged upon it. The resolution of the cross-correlation profile ('trace'), therefore, was necessarily worse than that of the spectrum itself by a factor of the order of $\sqrt{2}$. In contrast, a spectrum that is directly recorded does not need to be degraded to be cross-correlated, as a numerical mask can consist, if desired, of delta-functions. It might also be pointed out, in extenuation, that at the time that the original spectrometer[31] was developed (and for many years afterwards), the only practical method of recording spectra was by photography, a slow and fraught process that involved the addition of a lot of noise to every resolved element.

New radial-velocity observations

In this section we describe successively the McDonald observations, the discovery of the SB2 nature of the B component, the distinction between Ba and Bb, and the methods for measuring radial velocities in spectra with so many components, before presenting the velocities themselves.

The observations have been made by J.T. with the 2·7- and 2·1-m telescopes at McDonald Observatory. The first 26 observations, taken in the interval 1995–1999, were made with the *2dcoudé* échelle spectrometer[37] at the coudé focus of the 2·7-m telescope; they have a resolving power of 60 000 and nearly unbroken wavelength coverage from about 4000 to 9000 Å. An exception was the first observation, which used a much smaller CCD than the others; it has the same resolving power, but its wavelength coverage is restricted to 5500–8400 Å with substantial inter-order breaks. Three more 2·7-m observations were made in 2000, but during that year the programme was transferred to the 2·1-m telescope, which has been used with the *Sandiford* Cassegrain échelle spectrometer[38], which also gives a resolving power of 60 000 with complete wavelength coverage from about 5600 to 7000 Å. The total number of 2·1-m observations is 14.

The data were processed and wavelength-calibrated in a conventional manner with the IRAF package of programs. The initial measurements of the early McDonald observations showed the expected triple-lined spectra in which an isolated absorption line typically gives rise to a trio of lines with that of the slow-moving B component in the middle, straddled by the lines of the fast-moving Aa and Ab components. Two observations made in 1998 February near to a nodal passage in the A sub-system (when there is the maximum velocity separation between Aa and Ab), however, demonstrated that B is itself double-lined. That situation is illustrated in Fig. 1, which shows a slice of spectrum from λ6055 to λ6070 Å in the Sun and in the HD 30869 observation of 1998 February 8. Each of the two Fe I lines in the solar spectrum is matched by a quartet of lines in HD 30869, with the two outer lines of each quartet belonging to Aa and Ab and the two inner ones to Ba and Bb. It is also clear that Aa is rotationally broadened whereas the other three stars are all sharp-lined. When the earlier McDonald spectra were re-examined in the light of that discovery it was found that in all of them B appeared, to a greater or lesser extent, double-lined. The question upon which Griffin *et al.*[12] had been unable to adjudicate in 1985 was, therefore, answered in the opposite sense to the way that they had tentatively selected. It remained, however, to distinguish in each spectrum between the spectroscopic components of B, and to determine their orbit.

The identification of the Ba and Bb components is a non-trivial matter, in view of their both being sharp-lined and of the similarity of their line strengths. The weak, low-excitation-potential (EP) lines of neutral species like Fe and other iron-peak elements, which we will discuss shortly, are of very similar strength in the two B components, so much so that it is difficult to distinguish between them. Medium-strength, high-excitation lines of neutral species like Fe, however, are found to be stronger in one component than the other, so we labelled the one with the stronger lines, which is presumably the brighter primary, Ba, and the other one Bb. Once the distinction has been recognized, the greater strength of certain lines of Ba compared with Bb can be seen by inspection; the two Fe I lines in Fig. 1 are examples. Both are of medium strength; the λ6056-Å line has $\chi_l = 4{\cdot}73$ eV and the λ6065-Å one has $\chi_l = 2{\cdot}61$ eV. Those two lines and numerous others like them, therefore, were used to decide in each spectrum which suite of lines belongs to which component.

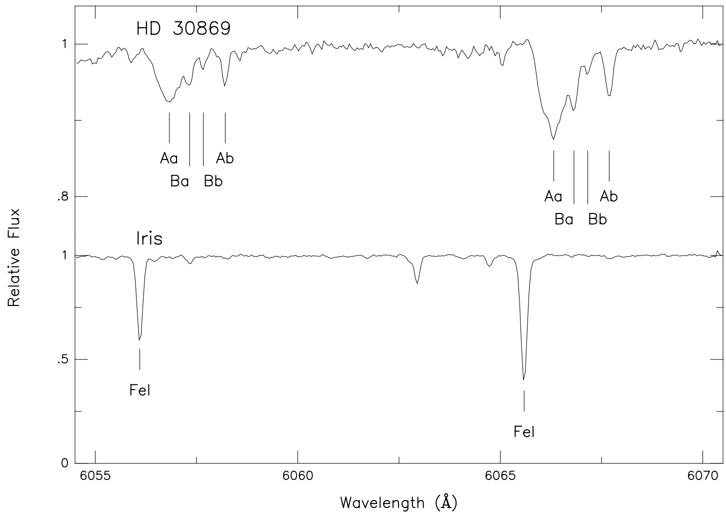

FIG. 1

The spectra of HD 30869 (top), and of sunlight scattered from the asteroid (7) Iris (bottom), from λ6055 to λ6070 Å. This stretch of the solar spectrum includes two medium-strength Fe I lines, but is otherwise fairly empty. The spectrum of HD 30869, which was observed on 1998 February 8 near maximum velocity separation of Aa and Ab, includes the same two Fe I lines, but each is seen to have four components — the fast-moving Aa and Ab components straddle the slower-moving B component which is itself seen to be made up of Ba and Bb components. The Aa spectrum is rotationally broadened ($v \sin i \sim 25$ km s^{-1}), while the spectra of the other three stars are all sharp-lined.

We next describe how we set about measuring the radial velocities so as to minimize the inevitable difficulties caused by mutual blending of lines in the quadruple-lined spectrum. Those blending difficulties are severe, especially since the Aa and Ab lines are usually closer together, and thus closer to the Ba and Bb lines, than they are seen in Fig. 1. In fact the usual situation is for all three sharp lines, Ab, Ba, and Bb, to be superimposed on the broad profile of their counterpart Aa line. Clearly it would help if one could find lines of Aa whose counterparts in the three cooler stars, Ab, Ba, and Bb, are of insignificant strength. Such lines would provide good radial velocities for Aa regardless of whether or not their negligible counterparts were blended with them. Fortunately, such lines are available: they are high-excitation lines belonging to majority species. The freedom to pick and choose between lines of differing characters represents a second crucial advantage (after the freedom from degradation of resolution by a mask) of an observation of the actual spectrum in comparison with that of a cross-correlation function.

The five high-excitation lines that have been used to measure the Aa radial velocities are the Si II lines at λ6347 Å ($\chi_l = 8 \cdot 12$ eV) and λ6371 Å ($\chi_l = 8 \cdot 12$ eV) and the O I triplet lines at λ7770 Å ($\chi_l = 9 \cdot 14$ eV). Fig. 2 shows the λ6347-Å Si II line in Aa and the absence of its counterparts in the other three stars. Continuing the exploitation of the temperature difference between Aa and the other stars, we can search for lines which are absent in Aa but present in Ab, Ba, and Bb. Such lines would make the measurement of radial velocities for Ab, Ba, and Bb much easier because blending with Aa would not present a difficulty. Fortunately, such lines, too, exist. They are weak, low-excitation lines of neutral

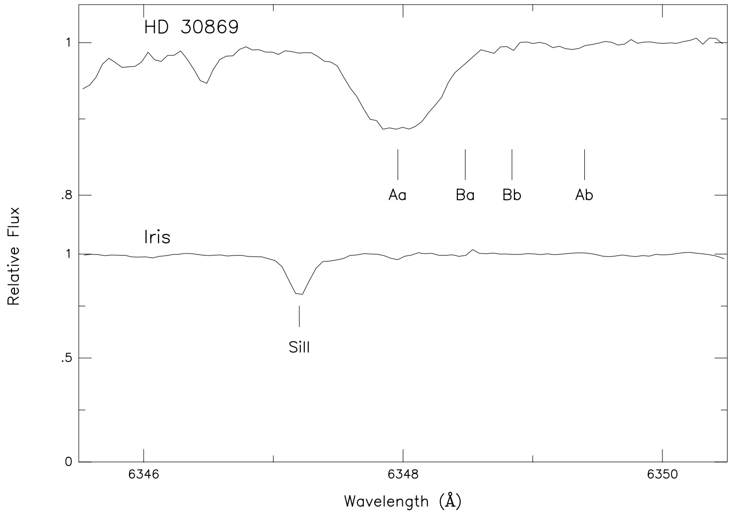

FIG. 2

The λ6347-Å Si II line in HD 30869 (top) and the Sun (bottom). The HD 30869 observation is another part of the same one that is shown in Fig. 1. In the Aa component the broad Si II line is manifest, but in the other three stars its counterparts, whose expected locations are marked, are undetectably weak. The Aa Si II line, therefore, is not distorted by its counterparts in the other three stars and so allows direct and reliable measurement of Aa radial velocities.

species, like Fe I, where the neutral species is the minor one and the ionized species the major. Lines of that type were the first choice for measurement of the Ab, Ba, and Bb radial velocities. Those most often called upon were the λ6039-Å V I line ($\chi_l =$ 1·06 eV), λ6126 Ti I (1·07 eV), λ6151 Fe I (2·18 eV, weak Aa line present), λ6327 Ni I (1·68 eV, weak Aa line present), λ6572 Ca I (0·00 eV), and λ6710 Fe I (1·48 eV). Fig. 3 shows the λ6039-Å V I line; weak, but distinct, lines of Ab, Ba, and Bb are present, while no Aa line is seen.

With that strategy, plus the fitting of multiple Gaussian profiles to the many remaining cases of blended lines, we were able to measure the radial velocities of a surprisingly large fraction of the components in our spectra of HD 30869; radial velocities of at least two stars were obtained in all of the observations and those of all four were measured in the majority of them. The dates of observation and the measured radial velocities are given in Table I. They are absolute radial velocities measured in the same way as described in earlier papers[39] in this series. We shall have occasion to describe the other columns of Table I in the section on the orbital solution below. The civil dates given in Table I correspond to the actual times of observations corrected to the Sun; the Julian dates incorporate a further correction to the barycentre of the HD 30869 system. That correction, which approaches 100 minutes for the A component and 160 minutes for B towards the end of the series of observations, can be somewhat significant: near periastron in the inner orbit, component Ab can accelerate by nearly 0·3 km s^{-1} during the correction interval — not incomparably less than the r.m.s. residual (0·5 km s^{-1}) of the McDonald measurements of its velocity.

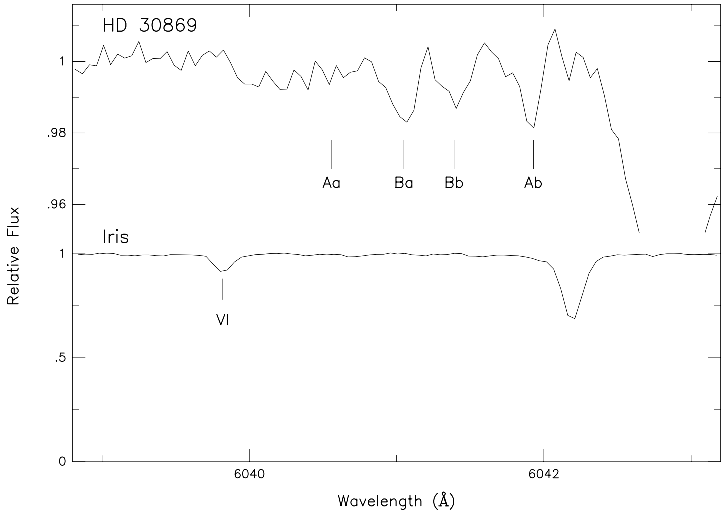

FIG. 3

A weak low-excitation V I line at λ6039 Å in HD 30869 (top) and the Sun (bottom). Again, the HD 30869 observation is the same as that in Fig. 1. Weak, but nonetheless distinct, features corresponding to the line in Ba, Bb, and Ab are seen, while there is no sign of the line in Aa. The V I line, therefore, provides for Ba, Bb, and Ab, not only for this but for all observations, radial velocities that are unaffected by blending with Aa.

At first sight it seems surprising that the V I line should have such similar strengths in the Ba and Bb components, whose mass ratio is as large as 1·19 (*cf.* Table II). It is the very property for which we selected the line — its rapid increase of strength towards later types — that is responsible for its near-equality in the two stars; reference to the spectra of the standards shows that its intrinsic intensity nearly doubles in the interval between the types of Ba and Bb.

At the risk of adulterating the good McDonald data, we have added to Table I such velocities as have been measured for Aa and Ab with other spectrometers (ones that utilize analogue masks) in the vicinities of the nodal passages that occur near periastron. At such times the cross-correlation signature of Ab is often nearly free of blending, and blending of Aa is restricted to the part of the profile well up on the redward wing, as illustrated in Fig. 22 of ref. 12. Additional observations made with the same instruments at other phases in the spectroscopic orbit of the A sub-system have proved to be effectively irreducible and are not listed, and all traces obtained with the spectrometer at the DAO have had to be abandoned owing to our inability to disentangle multiple dips that are compounded with the asymmetrical instrumental profile of that spectrometer. Velocities obtained at Cambridge have been adjusted by $-0{\cdot}8$ km s^{-1} and those from Palomar by $-1{\cdot}1$ km s^{-1}, in conformity with the discussion on p. 9 in the first paper[40] of this series; no adjustment has been applied to measurements made with the Haute-Provence *Coravel*. It might be mentioned that the ensemble of nodal traces obtained at Haute-Provence and Cambridge provides convincing evidence for the duplicity of B, but no overview of those traces had been undertaken before news of the McDonald discovery was received in Cambridge, and it is very doubtful whether even the period, let alone any sort of orbit, could have been established for B from such material.

Table I

Radial-velocity observations of HD 30869

All velocities are of positive sign, and were obtained at McDonald Observatory except as indicated. McDonald observations were given weights 1 and 2 for the primary and secondary, respectively, in the solution of the A sub-system, and were equally weighted in the solution of the B sub-system.

Date (UT)	*JD*	*Radial velocities (km s⁻¹)*				*Phases*			*Residuals (km s⁻¹)*			
	−2 400 000	*Aa*	*Ab*	*Ba*	*Bb*	*AB*	*A*	*B*	*Aa*	*Ab*	*Ba*	*Bb*
1980 Oct. 22·56★	44535·04	13·5	—	—	—	·987	0·971	—	+0·7	—	—	—
23·30★	535·78	11·9	—	—	—	·987	·976	—	−1·0	—	—	—
24·29★	536·77	13·3	80·7	—	—	·987	·983	—	−0·1	+0·6	—	—
25·28★	537·76	14·7	—	—	—	·987	·990	—	+0·2	—	—	—
1983 Dec. 1·03†	45669·52	20·4	—	—	—	·020	8·872	—	−2·8	—	—	—
3·05†	671·54	18·1	—	—	—	·020	·886	—	−3·3	—	—	—
11·02†	679·51	8·8	—	—	—	·020	·942	—	−4·1	—	—	—
1986 Sept. 19·20†	46692·71	12·3	—	—	—	·049	15·998	—	−1·7	—	—	—
1987 Jan. 28·96†	46824·47	13·3	—	—	—	·053	16·916	—	−3·9	—	—	—
30·88†	826·39	13·2	—	—	—	·053	·929	—	−1·9	—	—	—
31·93†	827·44	12·8	—	—	—	·053	·937	—	−1·1	—	—	—
1989 Jan. 22·95†	47549·47	8·0	—	—		·074	21·965	—	−3·2	—	—	—
Oct. 31·14‡	830·67	15·2	69·0	—	—	·082	23·924	—	−1·6	−2·0	—	—
Nov. 1·13‡	831·66	13·9	70·7	—	—	·082	·931	—	−1·8	−2·0	—	—
6·10†	836·63	9·6	—	—	—	·082	·965	—	−1·9	—	—	—
1992 Dec. 22·01‡	48978·55	18·2	70·5	—	—	·115	31·918	—	−0·4	−0·1	—	—
1994 Dec. 10·11‡	49696·66	19·7	73·7	—	—	·136	36·919	—	+0·8	+2·3	—	—
11·08‡	697·63	17·7	75·4	—	—	·136	·926	—	−0·1	+2·4	—	—
12·06‡	698·61	15·5	77·2	—	—	·136	·933	—	−1·3	+2·5	—	—
13·08‡	699·63	14·4	76·5	—	—	·136	·940	—	−1·3	+0·1	—	—
14·00‡	700·55	16·2	81·1	—	—	·136	·946	—	+1·4	+3·3	—	—
1995 Jan. 23·11	49740·66	49·9	22·6	—	—	·137	37·226	—	−0·5	−0·3	—	—
Aug. 9·44	938·99	42·9	34·0	42·0	51·9	·143	38·607	0·966	−0·3	−0·2	+0·3	−0·9
Sept. 30·44	990·99	12·9	80·9	50·1	43·6	·144	·969	1·070	0·0	−0·2	+0·3	+0·6
Oct. 1·43	991·98	13·2	80·8	50·4	43·1	·144	·976	·072	+0·2	−0·2	+0·5	+0·2
12·47	50003·02	37·5	—	49·9	—	·145	39·053	·094	+1·5	—	−1·3	—
Dec. 2·44	053·99	49·2	25·7	53·4	38·1	·146	·408	·197	+0·5	−0·3	−0·4	0·0
3·37	054·92	48·8	25·9	53·8	37·8	·146	·414	·199	+0·3	−0·3	0·0	−0·3
1996 Jan. 4·36	50086·91	43·3	—	53·0	—	·147	39·637	1·263	+1·1	—	−0·4	—
5·37	087·92	42·7	—	52·2	—	·147	·644	·265	+0·8	—	−1·2	—
6·31	088·86	42·1	—	53·2	—	·147	·651	·267	+0·4	—	−0·2	—
Feb. 6·22	119·77	26·5	59·2	52·1	39·0	·148	·866	·330	−0·2	−0·8	−0·2	−0·8
9·17	122·72	23·5	64·0	52·2	40·2	·148	·887	·335	−0·5	−0·1	0·0	+0·3
Nov. 28·00§	415·56	17·0	71·6	—	—	·157	41·926	—	−1·3	−1·8	—	—
30·09§	417·65	15·1	77·3	—	—	·157	·941	—	−0·9	+0·4	—	—
Dec. 2·00§	419·56	13·8	79·7	—	—	·157	·954	—	−0·5	+0·1	—	—
5·00§	422·56	12·8	80·9	—	—	·157	·975	—	−0·4	−0·4	—	—

TABLE I (*concluded*)

Date (UT)	*JD* − *2 400 000*	*Radial velocities (km s⁻¹)* *Aa*	*Ab*	*Ba*	*Bb*	*Phases* *AB*	*A*	*B*	*Residuals (km s⁻¹)* *Aa*	*Ab*	*Ba*	*Bb*
1997 Sept. 15·10‡	50706·66	13·1	78·3	—	—	·165	43·953	—	−1·4	−1·4	—	—
1998 Feb. 4·08	50848·64	16·5	77·4	38·1	55·2	·169	44·942	2·797	+0·5	−0·1	−0·6	+0·5
8·09	852·65	13·4	81·5	38·1	55·1	·169	·970	·805	0·0	−0·1	−0·4	+0·2
Apr. 7·15	910·71	49·1	25·4	38·2	55·1	·171	45·375	·922	−0·6	−0·2	−0·4	+0·4
8·14	911·70	48·9	25·6	38·1	54·8	·171	·381	·924	−0·7	−0·1	−0·6	+0·2
13·13	916·69	48·2	26·7	38·1	54·7	·171	·416	·934	−0·8	−0·1	−1·0	+0·6
1998 Oct. 1·49	51088·05	44·4	36·0	52·1	—	·176	46·610	3·279	+0·6	+1·0	−0·3	—
2·50	089·06	44·1	36·1	52·7	—	·176	·617	·281	+0·6	+0·7	+0·3	—
5·51	092·07	43·3	36·8	52·1	—	·176	·638	·287	+0·6	+0·2	−0·2	—
Nov. 26·38	143·94	16·9	75·9	50·1	41·5	·178	·999	·391	−0·3	−0·1	0·0	+0·9
27·42	144·98	19·7	72·5	49·5	40·1	·178	47·006	·393	+0·2	0·0	−0·6	−0·5
1999 Feb. 6·11	51215·67	46·8	29·4	45·7		·180	47·498	3·536	−0·4	−0·4	—	—
Mar. 8·09	245·65	40·8	43·0	—	49·3	·180	·707	·596	+1·1	+1·5	—	+2·0
11·21	248·77	40·0	44·7	—	—	·181	·729	—	+1·5	+1·4	—	—
Nov. 2·34	484·90	50·1	26·0	49·4	42·0	·187	49·373	4·078	+0·1	+0·2	+0·3	+0·7
2000 Feb. 1·23	51575·79	18·7	72·6	52·5	36·5	·190	50·006	4·261	−1·1	+0·1	+0·2	−0·8
3·13	577·69	24·1	64·6	51·8	37·3	·190	·020	·264	−0·7	−0·2	−0·5	−0·1
Oct. 26·46	844·03	25·7	62·0	37·9	54·3	·198	51·875	·801	−0·8	−0·5	0·0	+0·2
Nov. 3·07§	851·64	19·2	76·4	—	—	·198	·928	—	+0·5	+1·9	—	—
4·12§	852·69	17·5	77·5	—	—	·198	·935	—	−0·1	+1·2	—	—
11·46	860·03	15·3	80·5	36·3	54·5	·198	·986	·833	+0·5	0·0	−1·0	−0·2
13·11§	861·68	16·9	77·2	—	—	·198	·998	—	−0·3	+0·3	—	—
13·44	862·01	18·1	76·0	36·5	54·4	·198	52·000	·837	+0·3	+0·1	−0·8	−0·4
15·06§	863·63	21·3	70·8	—	—	·198	·011	—	−0·3	+0·7	—	—
17·07§	865·64	27·8	61·5	—	—	·198	·025	—	+0·7	−0·1	—	—
Dec. 2·30	880·87	48·2	28·3	37·2	55·1	·199	·131	·875	−0·8	+0·4	+0·1	+0·1
5·34	883·91	—	25·9	37·3	54·9	·199	·152	·881	—	−0·3	+0·2	−0·1
7·42	885·99	50·0	26·0	37·9	54·8	·199	·167	·885	−0·6	+0·6	+0·8	−0·1
8·28	886·85	49·6	24·8	37·5	54·5	·199	·173	·887	−1·2	−0·3	+0·4	−0·4
9·41	887·98	50·2	24·6	37·3	55·0	·199	·181	·889	−0·8	−0·2	+0·1	+0·1
14·29	892·86	51·1	24·0	37·8	54·8	·199	·215	·899	−0·3	−0·1	+0·5	+0·1
2001 Jan. 12·31	51921·88	48·5	26·7	38·4	51·3	·200	52·417	4·957	−0·9	−0·5	−1·2	−0·6
Mar. 13·13	981·70	32·3	56·1	50·5	42·3	·202	·833	5·078	+1·2	+0·6	+1·7	+1·4
Aug. 25·15§	52146·72	14·7	81·5	—	—	·206	53·983	—	+0·2	+0·2	—	—
2002 Feb 2·22	52307·79	46·3	31·5	40·4	51·3	·211	55·104	5·734	−0·6	−0·1	+1·0	−0·4
Dec. 1·42	609·99	51·3	24·8	50·0	38·2	·220	57·209	6·343	−0·4	+0·3	−0·3	−0·1
2003 Mar. 21·17	52719·74	14·4	82·2	—	—	·223	57·973	—	+0·2	−0·2	—	—
2005 Oct. 18·47	53662·04	—	32·1	47·4	42·4	·250	64·536	8·460	—	−0·3	+0·6	+1·2

*Observed with the Palomar 200-inch telescope; weight 1 (primary), 0·5 (secondary).
†Observed with the original radial-velocity spectrometer at Cambridge; weight 0.
‡Observed with the Haute-Provence *Coravel*; weight 0.
§Observed with the Cambridge *Coravel*; weight 1 (primary), 0·5 (secondary).

Spectral types

None of the authors is normally involved with spectral classification (or, therefore, possesses appropriate materials or skill to do it well), so we hope that it is understandable that our efforts here in that direction are of rather a makeshift character. In the first place, we had no McDonald spectra of standard stars comparable with the broad-lined F-type Aa component of HD 30869, so we were unable to make our own estimate of its spectral type. Since that component is by far the brightest, especially in the violet region of the spectrum where classifications have normally been made, it has seemed tolerably fair to adopt the type of F5 given (by no less an expert than Morgan[41]) for the system as a whole. It might well be argued that, since that classification included the three companion stars of much later type it must imply that Aa is actually slightly earlier, say F4. Since we are in any case not able to offer an independent *spectral* classification, it is perhaps admissible to refer to relevant non-spectroscopic evidence. Thus we remark that, in the *Discussion* section below where we give a photometric model of the system, it will be seen to be the reverse of helpful to adopt a type that would make Aa any brighter than corresponds to the type of F5 V, which we therefore recommend as representing the Aa component.

We also lacked spectra of suitable single-star standards to compare with the narrow-lined G- and K-type Ab, Ba, and Bb components, but we have pressed into service the McDonald spectra of four G- and K-type Hyades main-sequence binaries in which we have taken an interest. Although binaries obviously make less-than-ideal standards, the companion stars in the four systems (HD 28545, G8 V; HDE 284414, K2 V; HD 29608, K3; and HDE 285947, K5 — van Bueren[2] 182, 43, and 185, and Johnson[42] 304, respectively) are all much fainter than their primaries, so for classification purposes they might serve as single stars. HD 29608[43] and HDE 285947[40] both harbour a third star, but those companions, too, are relatively faint. In order to extend the spectral-type range of the standards we also included the Sun (G2 V), for which we had a readily available McDonald spectrum.

Since we were working with high-resolution spectra, instead of at the rather low dispersions normally used in classification, we estimated the spectral types of Ab, Ba, and Bb by examining pairs of lines whose relative strengths vary quickly with type. Three lines were used: a low-EP line (λ6039 Å V I, *cf.* Fig. 3), which strengthens rapidly towards later types, and two high-EP lines (λλ6027 and 6380 Å Fe I), which strengthen only gradually. Those particular lines were chosen on account of their isolation, which facilitates the measurement of their equivalent widths, especially in the inevitably crowded spectra of HD 30869. The equivalent widths of the three lines in Ab, Ba, and Bb were measured in seven spectra in which the Aa and Ab components were well separated, thus minimizing mutual blending, and an average equivalent width for each line in each component determined. The equivalent widths of the lines in the standard stars were similarly measured. We then determined ratios of equivalent widths for the two pairs of lines 6039/6027 and 6039/6380 in each component and in the standard stars. We note that for any particular component the line ratios are independent of the (quite uncertain) contribution that the relevant component makes to the total light of the system, because that factor cancels out in the ratio. The same holds true in the standard stars — the small effect of the faint secondary on the equivalent width of the bright primary cancels in the line ratio. Both line ratios increase by approximately a factor of five in going from the Sun (G2) to HDE 285947 (K5) and are thus sensitive measures of spectral type.

Interpolation of each component's line ratios in the relationships between the line ratios and spectral type for the standard stars then provided the component's spectral type. For Ab both line ratios fix the spectral type at G8, while for Ba the 6039/6027 ratio indicates a K2 type and the 6039/6380 ratio indicates K1, and for Bb the 6039/6027 ratio suggests a K7 type and the 6039/6380 ratio K5. (The K7 type proposed for Bb from the 6039/6027 ratio involves a small extrapolation of the calibration of the ratio.) We obtain, therefore, spectral types of G8 for Ab, K1 or K2 for Ba, and K6 for Bb; we consider the type of Ab to be well determined, while those of Ba and Bb are comparatively uncertain.

Solution of the orbits

The data of Table I can be introduced directly into separate orbital solutions for (Aa + Ab) and for (Ba + Bb), *i.e.*, for the A and B sub-systems. Those solutions, performed with the normal double-lined orbit-solving program, look quite tolerable, but the residuals in both cases exhibit systematic trends, upwards for A and downwards for B. The trends evidently reflect variations in the γ-velocities — the motions of the centres of mass of the respective binaries in what we term the 'outer', or 'visual', ~100-year orbit. That orbit is of quite high eccentricity (~0·6), and as luck would have it there was a periastron passage and nodal passage early in the time interval spanned by our observations. We allowed ourselves to hope that, although we had covered only a rather small part of the orbit, our observations might allow us to make some sort of determination of the outer orbit without depending upon the 'visual' data apart from fixing the period, which would obviously not be determinable from the velocities alone.

We tried, as a starting point, imposing upon the γ-velocities the velocity variations implied by the most recently published visual orbit, that of Söderhjelm[20]; we were obliged to estimate the velocity amplitudes which would correspond to reasonable masses for the component stars and which indeed would not be too far out of line with the mass sum of 3·11 $M_\odot$ derived by Söderhjelm from his elements plus the *Hipparcos* parallax. We found that the apparent variation of the γ-velocity of the A sub-system, particularly as charted by the velocities of Aa measured at several different nodal passages in the 1980s with the original radial-velocity spectrometer[31] at Cambridge, showed a serious systematic departure from the proposed ephemeris. The run of the velocities appeared to require either a major increase in the eccentricity of the outer orbit or else an unacceptably high velocity amplitude. Unfortunately the more accurate McDonald observations do not cover a sufficiently long time interval to provide a prescriptive value for the slope of the γ-velocity variation (or, therefore, for the radial-velocity amplitude in the outer orbit) for either of the sub-systems.

Experimentation with the elements of the visual orbit convinced us that changes that would go any significant way towards accommodating the discrepancies noticed in the Cambridge velocities would entirely vitiate the accord of the orbit with the visual and other astrometric observations that underlay it. It became evident that, so far from attempting to derive the elements of the outer orbit from our own data, we would do best to impose the visual elements upon our solutions for the sub-systems. One of the other things that we discovered, however, in the course of our experiments was that the relative orbit of the visual components of HD 30869 has exhibited small but significant deviations from the path foreseen according to Söderhjelm's elements, so as part of our investigation here we have re-determined the elements of the outer orbit.

The 'visual' orbit

In Table II we list the observational material available for the solution of the visual orbit. In accordance with normal practice in this field, the majority of the data are presented as 'normal places' in which several observations (often by a number of different observers) are averaged together over an interval of time such that the on-going motion of the system does not contribute significant error to the average. The observers' names are abbreviated in the conventional fashion[44]. Most of the normal places for the visual observations have been given by Heintz[18]; a comprehensive listing of the measurements, from the records maintained in Washington by the US Naval Observatory, has been sent to us by G. Wycoff.

In the determination of the orbit the normal places were weighted according to the precepts laid down with characteristic conciseness by Heintz in the second paragraph on p. 46 of his book[45]. The uncertainties of the individual observations that were combined into the normal places were also evaluated according to the proposals made by Heintz in the first complete paragraph on p. 24 of the same work, *viz.*, that for separation ρ the uncertainty for a single observation is $C\rho^{1/3}$, where the constant C can take different values according to the skill of the observer but for a good measurement is taken as 0″·08, while the uncertainty in position angle ($\rho\Delta\theta$) is taken as 0″·03. For speckle measures the uncertainty can best be specified in cartesian rather than polar coordinates; it is taken to be 0″·005 in dx and dy for observations made with telescope apertures of 2 metres or more, and to be 0″·01–0″·03 for smaller apertures. Still in conformity with Heintz's (p. 46) ideas, the weighting of all angular-separation data in the case of the visual observations (only) has been decreased by a factor of 5. We give explicitly in Table II the results of applying those principles to the material at hand for the solution of the orbit of HD 30869, by the inclusion of columns showing the weight that has thereby been assessed for each datum. The actual calculation of the orbit was performed by the method of differential correction in polar coordinates[46], and resulted in the following elements:

P = 95·10 ± 0·15 years	i = 51·3 ± 0·6 degrees
T = 1982·02 ± 0·06	ω = 310·0 ± 0·7 degrees
a = 0·731 ± 0·007 arcsec	Ω_{2000} = 142·4* ± 0·7 degrees
e = 0·597 ± 0·004	*(*ascending* node)

The uncertainties of the elements were obtained by the covariance matrix of the normal equations and the sum of the residuals in position angle and separation. Fig. 4 depicts the apparent relative orbit as it is seen on the sky, with each symbol representing an observed normal place connected to the corresponding computed position for its date.

The elements yield a value for a^3/P^2 of (4·32 ± 0·12) × 10^{-5} in Solar System units; in conjunction with the *Hipparcos* parallax of 0″·02391 ± 0″·00104, they give Σm = 3·16 ± 0·41 $M_\odot$. The standard deviation of the mass sum has been derived in the manner indicated by Argyle, Alzner & Horch[47]; the principal contribution to it comes from the uncertainty in the parallax.

TABLE II

'Normal places' (observed position angles and separations) for the 'visual' orbit

Year	*P.A.* (*2000*) °	*Sep*^{n} ″	*Weights P.A.*	*Weights Sep*^{n}	*Measures*	*Residuals P.A.* °	*Residuals Sep*^{n} ″
Visual measures							
1890·93	155·0	0·31	1·80	0·62	Sp8, Bu8	+4·0	−0·06
1895·22	178·3	0·37	5·94	0·76	Sp10, Bar2	−0·4	−0·05
1897·64	192·8	0·42	11·10	2·22	A11, Hu4, Sp2, L2	+0·8	−0·02
1900·09	204·3	0·45	12·17	2·43	A9, Doo5, See4, L3	0·0	−0·01
1903·34	218·6	0·45	14·11	1·25	A10, Com4, Doo2, VBs2, Bu2	−0·3	−0·04
1908·35	238·5	0·53	11·25	2·25	Doo5, A3, Com2, VBs1, L1	+1·3	−0·03
1914·96	253·9	0·63	14·96	2·99	VBs6, A4, Com3, Fox2	−1·1	−0·04
1919·79	264·9	0·67	11·70	1·04	VBs9, A6	+0·1	−0·08
1924·84	271·2	0·79	5·00	2·69	A4, B4, Fur2, Cull1	−1·9	−0·03
1932·21	282·9	0·91	29·28	5·86	B7, Baz4, VBs3, Fur1, Cull1, StG2, Smw1, Fin1	−0·1	0·00
1938·00	289·1	0·95	41·18	8·23	Rab12, Smw8, Dur7, Vou4, VBs3, Baz3	−0·6	−0·01
1942·93	294·5	0·99	39·76	7·95	Rab17, VBs4, Vou4, Baz4, Ol3, B1	−0·4	0·00
1950·87	302·4	0·99	30·26	6·05	Rab30, Baz6, B2	−0·7	+0·01
1956·47	309·4	0·95	34·85	6·97	Rab26, Wor9, Cou3, B3	+0·2	+0·01
1960·97	316·3	0·94	31·00	2·76	Hei10, Baz4, B4, Wor3, Cou3, Hln1	+1·6	+0·06
1964·30	318·4	0·88	13·45	1·19	Wor4, Wak4, Baz3	−1·0	+0·07
1968·10	327·1	0·76	14·28	1·28	Hei8, Wor4, Baz4	+1·0	+0·06
1971·33	332·6	0·62	9·38	1·88	Baz4, Wor3, Hei3	−1·4	+0·03
1974·64	353·5	0·48	0·45	0·48	Hln2, Mlr2, Beh1	+6·5	+0·05
1976·33	356·3	0·36	4·05	0·81	Wor5, Hei3	−2·1	+0·01
1982·86	119·3	0·26	1·30	0·26	Hei3	+0·1	−0·01
1988·37	165·2	0·41	4·14	0·83	Hei4, Gii2	−1·8	+0·01
1992·55	192·1	0·45	2·59	0·52	Hei4	+1·1	+0·01
1995·39	211·4	0·49	0·20	0·25	Alz2	+6·1	+0·03
2004·94	243·7	0·58	0·20	0·16	Alz1	+1·9	−0·01
Speckle measures							
1979·86	56·4	0·212	2·82	2·82	Heg4	+1·1	+0·012
1980·73	78·2	0·224	5·00	2·22	McA2	+0·6	+0·022
1980·94	82·8	0·211	2·37	2·37	Ebe3	0·0	+0·006
1982·76	119·4	0·264	3·20	4·20	McA1	+1·6	0·000
1983·05	120·7	0·267	4·20	4·20	McA1	−1·1	−0·008
1984·05	134·2	0·306	5·00	5·00	McA1	+0·6	−0·006
1985·84	147·5	0·355	3·20	5·62	McA1	−2·0	−0·006
1986·88	155·2	0·373	3·20	5·90	McA1	−2·0	−0·008
1987·76	162	0·401	6·30	6·30	McA1	−1·1	+0·007
1988·16	166·1	0·402	11·02	11·02	McA3	+0·4	+0·003
1988·80	175	0·36	0·45	1·00	Iso1	+5·3	−0·05
1988·91	168·8	0·408	6·50	6·50	McA1	−1·6	+0·001
1989·19	172·2	0·418	16·20	16·20	McA6	+0·2	+0·008
1990·27	178·5	0·424	9·50	9·50	Hrt2	+0·1	+0·004
1990·76	182·6	0·429	6·83	6·83	Hrt1	+1·4	+0·005
1991·25	184·0	0·430	6·83	6·83	Hip	0·0	+0·002
1991·90	185·4	0·452	7·20	3·17	Msn1	−2·1	+0·019
1995·87	207·0	0·460	5·00	4·00	Pat1	−0·6	−0·007
1996·87	211·9	0·469	7·44	7·44	Hrt1	−0·2	−0·008
1997·83	217·3	0·489	13·45	13·45	Hor3	+1·0	+0·002
1998·69	219·8	0·503	7·94	7·94	Msn1	−0·1	+0·005
1999·78	224·7	0·51	12·48	5·76	Hor8	+0·4	0·00
1999·87	224·4	0·508	22·45	22·45	Msn1, Hor3	−0·2	−0·005
2000·77	229·0	0·523	8·29	8·29	Hor1	+1·0	0·00
2001·88	232·9	0·53	13·12	6·55	Hor10	+0·9	−0·01

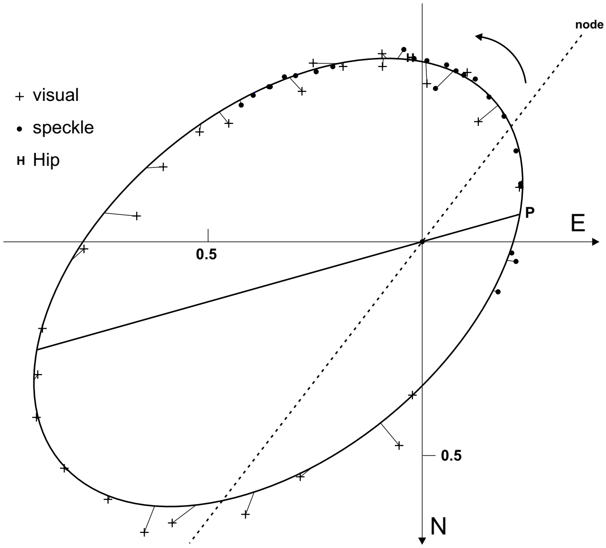

FIG. 4

The apparent relative orbit of the visual system HD 30869 AB. In conformity with the usual conventions, north is at the bottom, and the position of the primary component, A, is treated as fixed at the origin of the coordinate system; the *x* and *y* scales are in seconds of arc. The ellipse shows the computed relative path of B. The plotted points represent the 'normal places' listed in Table II; each of them is joined by a line to the computed position of B at the corresponding epoch. P identifies the periastron point; the line leading from it indicates the major axis of the true (non-foreshortened) ellipse. The dotted line is the line of nodes, *i.e.*, the line in which the orbital plane intersects the 'plane of the sky' (the plane normal to the line of sight); the orbital inclination of 51°·3 implies that the orbital plane is at that angle to the plane of the sky, the larger part of the orbit (to the left of the dotted line) being tipped away from us.

The spectroscopic orbits

The orbits of the two spectroscopic sub-systems have been solved separately by means of a program intended for use with that variety of triple systems in which a double-lined 'inner' binary exhibits a changing γ-velocity. The program allows the option, of which we avail ourselves here, of imposing fixed elements for the outer orbit, apart from what we call the 'grand' gamma-velocity, which we represent by the capital Γ. Having determined in the immediately previous section of this paper the geometrical elements of the outer orbit, we have to supply the radial-velocity amplitude in that orbit for each of the visual components, as the one remaining quantity needed to define the variation of the γ-velocity of the corresponding sub-system.

To enable us to assess the velocity amplitudes in the outer orbit, the following information is at hand (*a*–*c*) or needed (*d*):

(*a*) the total mass, noted above as 3·16 ± 0·41 $M_{\odot}$, suggested by the visual elements in conjunction with the parallax;

(*b*) the known inclination, 51°·3 ± 0°·6, of the outer orbit, which yields the value 0·475 for the factor $\sin^3 i$ that features in the expression for masses derived from radial-velocity amplitudes;

(*c*) the mass ratios (see below) for the individual inner orbits, about 1·54 for A and 1·19 for B, with negligible sensitivity to the values adopted for the amplitudes in the outer orbit. But:

(*d*) in order to specify the *relative* amplitudes of the two visual components, our only recourse is to assess the relative masses of those systems by appealing to our estimates of the spectral types of the four stars.

We start by implementing (*d*) in the light of (*c*) by assigning masses to the stars, as set out in the informal table below. The internal mass ratios Aa/Ab and Ba/Bb are well enough fixed by the spectroscopic *q* values, but the absolute values of the masses pose difficulties. The values that we propose are higher than those that would be adopted or interpolated from published tables such as that in *Astrophysical Quantities*[48], and indeed appear dangerously (1·5σ) high in relation to the mass sum found above from our own solution of the visual orbit. On the other hand, they are lower than the masses found, for example, in the directly comparable case of the Hyades eclipsing binary HD 27130 (van Bueren 22) which has been reported[12] to consist of components of types G6 V and K6 V — the latter being exactly the type we find above for HD 30869 Bb — where component masses of 1·04 and 0·75 $M_{\odot}$ were established[12] with very small uncertainties from the spectroscopic orbit.

Component		*Spectral*	*Masses*		
Visual	*Spectroscopic*	*type*	$M_{\odot}$	$M_{\odot}$	$M_{\odot}$
A	Aa	F5	1·4	2·3	3·78
	Ab	G8	0·9		
B	Ba	K1/2	0·8	1·48	
	Bb	K6	0·68		

Having thus tried to steer a middle course between Scylla and Charybdis, at the imminent risk of being thought to have foundered on one of them (if not indeed both!), we deduce from the penultimate column of the above table that the *q* value (K_B/K_A) in the outer orbit is 2·3/1·48, *i.e.*, 1·55, and we utilize the datum in item (*b*) above to find that the mass sum, $(m_1 + m_2)\sin^3 i$, to which the *K* values in the outer orbit must be tailored, is 3·78 × 0·475, or 1·80 $M_{\odot}$. To at least the accuracy warranted by this discussion, those parameters fix K_A at 3·9 km s^{-1} and K_B at 6·0 km s^{-1}. The velocity curves that correspond to the elements of the outer orbit, including those radial-velocity amplitudes, are plotted in Fig. 5, together with the observational data for the four components of HD 30869.

Once the outer orbit is established, the solutions of the inner ones readily follow. In the case of the B system, all of the observations come from the same source and give very similar r.m.s. residuals for the individual components, so all are weighted equally. For A, the principal (McDonald) series produces considerably smaller residuals for Ab than for Aa, no doubt owing to the sharpness of the lines of Ab in comparison with those of Aa despite the much greater strength of the Aa lines, so the Ab velocities have been given double weight. The measurements made near nodal passages with the Cambridge *Coravel* merit unit weight for Aa but only half-weight, *i.e.,* one quarter of the weight of the corresponding McDonald data, for Ab. We have preferred to disregard altogether the Haute-Provence measurements, which in any case would warrant very small weight, and the same is certainly true of the observations made with the original radial-velocity spectrometer at Cambridge, which refer only to component Aa and all of which deviate seriously from the velocity curve plotted in Fig. 5.

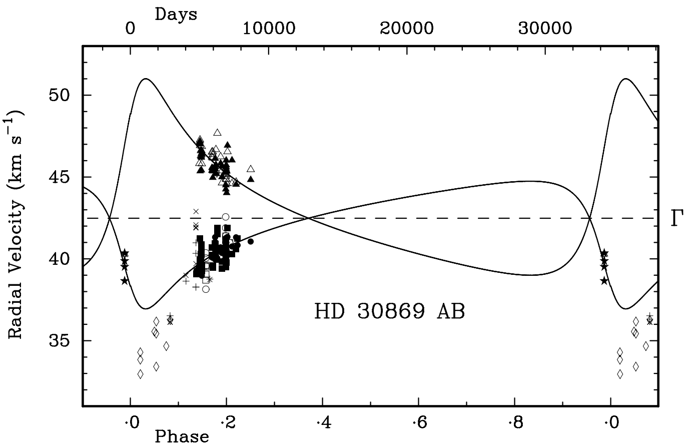

FIG. 5

Velocity curves, derived from the visual orbital elements and with the amplitudes fixed as described in the text, for the centres of mass of the two sub-systems, in the 'outer' or 'visual' orbit of HD 30869. The plotted points represent the velocities remaining after the motions in the spectroscopic orbits have been accounted for. The McDonald observations are represented by filled squares for component Aa, filled circles for Ab, filled triangles for Ba, and open triangles for Bb. No other source contributes any data on the B components, but velocities of Aa and Ab are shown as filled and open stars for Palomar observations (there is only one open star, largely hidden by the uppermost filled one), as plusses and crosses for Haute-Provence, as open squares and circles for the Cambridge *Coravel*, and as open diamonds for the original Cambridge spectrometer (Aa only).

TABLE III

Elements of the three orbits of HD 30869

Element	*Outer (AB)*	*Inner (A)*	*Inner (B)*
P (days)	34740	143·586 ± 0·007	496·7 ± 0·6
T (JD)	2444976	2451000·52 ± 0·09	2451446 ± 5
Γ (km s^{-1})	(+42·48)	+42·34 ± 0·07	+42·70 ± 0·08
K_1 (km s^{-1})	3·90	18·85 ± 0·11	7·69 ± 0·13
K_2 (km s^{-1})	6·00	29·06 ± 0·15	9·15 ± 0·22
q $(=m_1/m_2)$	1·55	1·542 ± 0·012	1·19 ± 0·03
e	0·597	0·540 ± 0·003	0·260 ± 0·012
ω (degrees)	130·0	218·3 ± 0·4	255 ± 4
$a_1 \sin i$ (Gm)	1494	31·32 ± 0·20	50·7 ± 0·9
$a_2 \sin i$ (Gm)	2299	48·28 ± 0·27	60·3 ± 1·4
$f(m_1)$ $(M_\odot)$	0·110	0·0595 ± 0·0011	0·0211 ± 0·0011
$f(m_2)$ $(M_\odot)$	0·402	0·218 ± 0·004	0·0355 ± 0·0025
$m_1 \sin^3 i$ $(M_\odot)$	1·095	0·593 ± 0·009	0·120 ± 0·007
$m_2 \sin^3 i$ $(M_\odot)$	0·712	0·384 ± 0·006	0·101 ± 0·005
R.m.s. residual (wt. 1) (km s^{-1})		0·69	0·65

The two lots of elements given by the solutions of the inner orbits are set out in Table III and illustrated in Figs. 6 and 7. We have added to the journal of radial-velocity observations given in Table I a column showing the phase in the outer

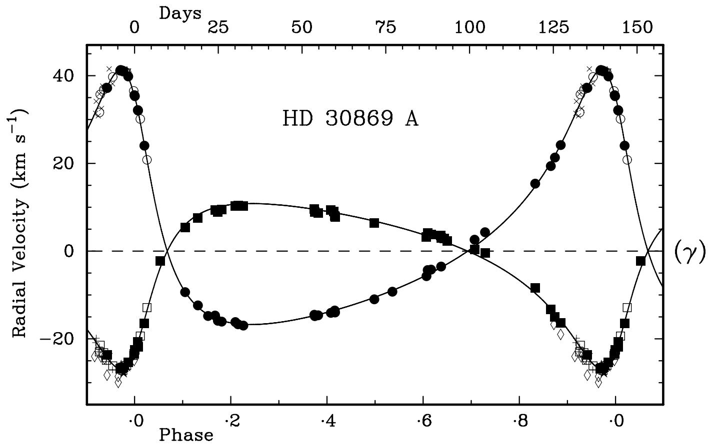

FIG. 6

The observed radial velocities of HD 30869 A plotted as a function of phase, with the velocity curves corresponding to the adopted orbital elements drawn through them. The computed variation in the γ-velocity arising from motion in the outer orbit has been allowed for, so the velocities are plotted here with respect to the centre of mass of the A sub-system (the visual primary). The meanings of the symbols are the same as in Fig. 5. The McDonald observations were weighted 1 for Aa and 2 for Ab in the solution of the orbit; the corresponding weights were 1 (Aa) and 0·5 (Ab) for Palomar and for the Cambridge *Coravel*, and zero for the original Cambridge spectrometer and for Haute-Provence.

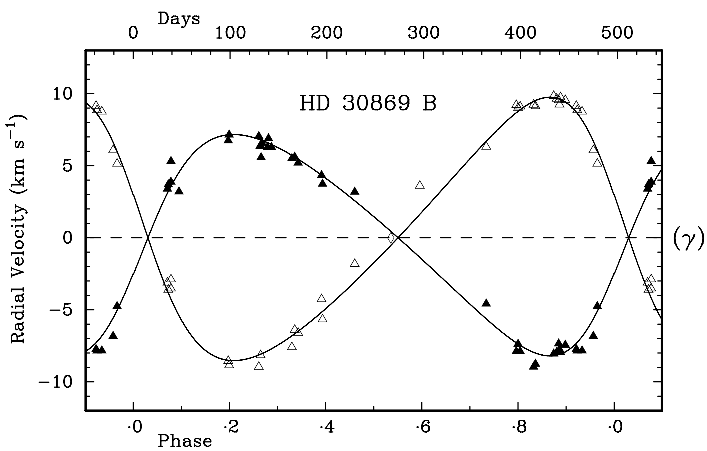

FIG. 7

The observed radial velocities of HD 30869 B plotted as a function of phase, with the velocity curves corresponding to the adopted orbital elements drawn through them. The diagram is exactly analogous to Fig. 6 but refers to the other visual component (the secondary). All the data are from McDonald and were equally weighted in the solution of the orbit. The filled symbols represent the primary, open ones the secondary.

orbit for each observation, two columns giving the phases in the inner orbits, and four columns showing the residuals from the computed velocities. Whereas the tabulated civil UT date in the first column of Table I is the actual time of observation, corrected only to heliocentric time, the Julian dates are those pertaining to the visual primary after correction for light-time across the visual orbit of HD 30869. Around phase ·025 in the inner orbit of A, the velocity of Ab is changing by more than 4 km s^{-1} per day, so the light-time correction, which reaches more than 0·07 day, represents an interval in which an appreciable change in velocity can take place. The inner orbits have both been computed with the corrected times; the difference between the tabulated civil time and the Julian date is of course in the opposite sense for B and is greater by the ratio of amplitudes (1·55). The Julian date appropriate to B is not separately listed in Table I, and its difference from the actual time of observation (though greater than for A) is less significant because the inner orbit of B has a longer period, smaller amplitudes, and lower eccentricity than that of A, so the maximum rate of change of velocity is much smaller.

Discussion

We comment first on the discrepancy between the Γ-velocities in Table III above. Each inner orbit produces its own value of Γ, but, since all the other elements of the outer orbit are imposed on the calculations, the value of that quantity is really only equivalent to some sort of mean value of the velocities measured for the sub-system, corrected according to the velocity curve enjoined by the imposed elements. It may be appreciated, by reference to Fig. 5, that an increase in K for either component would imply that the whole of the compact bunch of observations would be further away from the Γ-velocity, so such an increase in the adopted value of K_1 in the outer orbit would raise the resulting value of Γ, while increasing K_2 would reduce it. By actual experiment with the orbital solutions we find that a change of either amplitude by 1 km s^{-1} alters the derived value of Γ by 0·51 km s^{-1}. Viewed in that light, the similarity of the values derived from the separate orbits may be seen as rather good, despite the appearance of significance with which the small formal uncertainties endow the discrepancy. We have not seen fit to bring the two values together artificially by allowing such a consideration to colour our choices of K_1 and K_2.

We might furthermore point out that the solution of a double-lined orbit does not normally derive separate estimates of the γ-velocity for each component individually, so the reader may be excused for not having any feel for whether the discrepancy that might be an issue here is unusual or not. Where the components of a binary or multiple system are of different spectral types, there ought to be an actual *expectation* of a discrepancy of such a character, owing not only to a difference in gravitational red-shifts (of which a tabulation for various spectral types can be found in ref. 49), but more particularly to the difference in 'convective blue-shifts'. Such shifts, which represent differences between the true kinematic velocity of the centre of mass of a star and the velocity that could be expected to be found from a measurement of its spectrum, have long been recognized on the basis of theoretical models of stellar atmospheres*, and are quantitatively more than large enough to explain the discrepancy that concerns us here. Values of the order of 0·2 km s^{-1} for K dwarfs and as much as 1 km s^{-1} for Procyon, whose F5 type makes it analogous to HD 30869 Aa, have been proposed[50]. Indeed, it has

*The basic principle is easily explained. The stellar surface is covered (like the Sun's) with a granular pattern of convective columns. Columns which are rising and are therefore, in comparison with the body of the star, approaching the observer and accordingly giving blue-shifted spectra, are hotter and thus brighter than descending columns, so they contribute more than their fair share to the total light.

seemed remarkable that authors who have demonstrated such shifts on theoretical grounds have neglected to capitalize on a pre-existing empirical demonstration of exactly the effect that they claim, in connection with a Hyades-cluster radial-velocity survey[51] that is obviously especially germane to our concerns here.

The above discussion seemed so conclusive, even (or perhaps particularly!) to its own authors, that it would be nice to clinch it by demonstrating a significant difference of the expected sign between the individual γ-velocities of components Aa and Ab — or, as comes to much the same thing, a difference in their mean residuals — from the the solution of the inner orbit of the system containing the F star. It therefore came as something of a disappointment to the authors to find that the relevant orbital solution exhibits no such difference!

Since we feel some obligation to provide a single value for the Γ-velocity instead of leaving an ambiguity, we average the two values by splitting their difference in proportion to the gradients of their velocity curves, *i.e.*, in proportion to the amplitudes in the outer orbit. In that way we ensure that the adopted value of Γ is the velocity that both visual components have at the moments when their centre-of-mass velocities in the outer orbit are equal. It is $+42 \cdot 48$ km s^{-1}, and is so shown in Table III and Fig. 5.

We turn now to the construction of a photometric model for the HD 30869 system. In doing so we need to take notice of the Δm of $2^{m} \cdot 01 \pm 0^{m} \cdot 02$ found by *Hipparcos* to be the difference in the visual components. That magnitude difference is of course in the *Hp* magnitude system that was private to the satellite, but cannot be far from ΔV since *Hp* is not far from *V*. From the run of the published relationship[52] between $(Hp - V)$ and $(V - I)$ and the values that the latter quantity may be estimated to have for the separate visual components, we deduce that ΔV is likely to be smaller than ΔHp by about $0^{m} \cdot 05$, making it $1^{m} \cdot 96$ with an uncertainty of only a few hundredths of a magnitude. The *Hipparcos* catalogue itself has no entries for the *Tycho* magnitudes of the individual visual components, but that omission has been repaired by Fabricius *et al.*[53]; they have given V_T for the primary and secondary as $6^{m} \cdot 50$ and $8^{m} \cdot 45$, respectively, and B_T as $6^{m} \cdot 98$ and $9^{m} \cdot 47$. Application of the transformations recommended[52] in the *Hipparcos* catalogue gives the *V* magnitudes as $6^{m} \cdot 46$ and $8^{m} \cdot 36$ and *B* as $6^{m} \cdot 87$ and $9^{m} \cdot 28$, leading to $(B - V)$ colour indices of $0^{m} \cdot 41$ and $0^{m} \cdot 92$ for the respective components. Summing the magnitudes that are thus implied for the components gives $V = 6^{m} \cdot 29$, $(B - V) = 0^{m} \cdot 47$, close to the observed values[7] of $6^{m} \cdot 27$ and $0^{m} \cdot 50$.

In assigning absolute magnitudes and colours to the various components of HD 30869, we preferred to take notice of the relationships of those quantities to spectral types in the Hyades cluster rather than to adopt tabular values from a listing such as that in *Astrophysical Quantities*[48]; specifically, we utilized the listing by Morgan & Hiltner[41], but we updated the absolute magnitudes given there by substituting those computed from the individual parallaxes or (failing them) from the currently believed Hyades distance modulus. Although the resulting photometric values for Aa and Ab seemed perfectly plausible, those for the B sub-system did not, and we allowed ourselves to be swayed by other considerations.

Strict acceptance of the spectral types that we have reported results in a B component that is considerably too faint and too red to match the *Tycho* photometry to which reference is made in the last paragraph but one. We note also that the discovery that B is a double star does not invalidate the radial-velocity trace shown in ref. 12, Fig. 22, where the equivalent width of the B dip is as much as $1^{2}/_{3}$ times that of Ab. Because the B components are of considerably later types than Ab their intrinsic signatures on radial-velocity traces (those that they would give if they could be observed individually in isolation) must be stronger, but the two stars still need jointly to be at least as bright as Ab to be consonant with the observed trace. Another consideration is that it is hard to believe that there could be any difficulty — as we ourselves have reported above that there *is* — in distinguishing between the B components if their absolute magnitudes differ by as much as the difference in spectral types would warrant, although it is clear that there must be a substantial difference between the two stars to give such a large mass ratio as the observed 1·19.

We have therefore seen fit to adopt for Ba and Bb absolute magnitudes that seem reasonable in the light of criteria that are basically photometric rather than spectroscopic; having done so, we fix the colour indices at the values that correspond to the relevant magnitudes in Morgan & Hiltner's list[41] where also we can discover that the implied spectral types are about K1 and K3/4. The discrepancy from the spectroscopic classification of K1/2 for Ba hardly merits comment, but K3/4 sits less comfortably with the K6 classification of Bb. The errors of classification (if those are what they are) are probably to be understood as resulting mainly from our having to use binary or multiple stars as standards of spectral type. It was explained in the relevant section above that the use of line ratios obviates any systematic errors that would be caused by the lines of the measured component being diluted by the light of the other(s), both in HD 30869 and in the 'standard' stars. An error that is not corrected by that procedure, however, is the misclassifications of the standard stars themselves, since in each case we adopted the type that was assigned to the whole system as if it applied to the primary star alone, whereas in fact the primary must in every case be earlier than the apparent type of the integrated system.

In the informal table below, we have included the B and U magnitudes as well as the $(B-V)$ and $(U-B)$ colour indices, because although it is the indices that are the familiar means of expressing colours it is the actual magnitudes that have to be summed (conveniently by reference to the table in the *Skalnaté Pleso Atlas*[54]) to obtain the combined magnitudes of the various components. The table first gives the properties adopted for the spectroscopic components of the visual primary, then their sum (which should represent the properties of the visual primary as a single entity), then the same information for B, and finally the sum of A and B (the properties of the whole HD 30869 system according to this photometric model). It may be mentioned that we bore in mind the revised proposals given here for the types of the components when we assigned masses to them in the informal table given previously.

Component	*Type*	M_V	$(B-V)$	$(U-B)$	M_B	M_U
Aa	F5	3·4	0·44	0·00	3·84	3·84
Ab	G8	5·2	0·74	0·33	5·94	6·27
A		3·21	0·48	0·04	3·69	3·73
Ba	K1	5·7	0·87	0·55	6·57	7·12
Bb	K3/4	6·3	1·05	0·95	7·35	8·30
B		5·21	0·93	0·66	6·14	6·80
AB		3·05	0·53	0·09	3·58	3·67

Comparison of the model M_V with the measured[7] apparent magnitude ($6^m \cdot 27$) of HD 30869 indicates a distance modulus $(m-M)$ of $3^m \cdot 22$, which is to be compared with the value of $3^m \cdot 11 \pm 0^m \cdot 10$ — somewhat on the low side for a Hyades member — stemming from the star's *Hipparcos* parallax. The discrepancy is clearly without significance, being scarcely greater than the standard error arising from the parallax alone. Whatever the exact value of the currently preferred distance modulus of the Hyades, the $3^m \cdot 22$ that we have obtained for HD 30869 could be held to be consonant with it, since the angular distance of about $6^1/_2°$ (more than 0·11 radian) of HD 30869 from the apparent centre[12] of the cluster itself represents a tangential offset of more than 11% of the cluster distance; the same offset radially would produce a discrepancy of $0^m \cdot 22$ in the modulus.

The model colour indices of $0^m \cdot 53$ and $0^m \cdot 09$ are slightly redder than the observed[7] $0^m \cdot 50$ and $0^m \cdot 06$, but they could be corrected merely by the adoption of slightly bluer indices for the principal component — in fact there is no other way in which the $(U-B)$ index could be reduced sufficiently, or in which the visual primary could be made bluer in $(B-V)$ than the Aa component alone, as its *Tycho*-derived colour index implies. The difference in the model between the visual magnitudes of the components is exactly 2^m, reasonably close to the $1^m \cdot 96$ and $1^m \cdot 90$ deduced above from the *Hipparcos* and *Tycho* photometry, respectively. Thus the model reproduces all the observed facts quite well. Since we are in any case obliged to adopt colours measured for surrogate stars rather than the actual objects involved in HD 30869, we feel that any gains that could be made by tinkering with the model at the level of hundredths of a magnitude would be illusory.

We can estimate the orbital inclinations of the spectroscopic sub-systems by comparing the values of $m \sin^3 i$ determined from their orbits with the values we have adopted for the actual masses. For the visual primary (the A sub-system), $\sin^3 i \sim 0 \cdot 425$, so $\sin i \sim 0 \cdot 752$, $i \sim 49°$; for B, $\sin^3 i \sim 0 \cdot 149$, $\sin i \sim 0 \cdot 53$, $i \sim 32°$. It might be argued that the inclination that we find for the A sub-system is near enough to that of the visual orbit (51°) for there to be a possibility that the two are co-planar (an idea already put forward by Turner *et al.*[28]), although there can be no guarantee that they are anywhere near to that condition since we have no information about the direction in which the spectroscopic orbit is tipped. (We also lack an intuitive feel for whether the orbital planes would remain stably related to one another in the long term, whether co-planar or not.) We can be sure that the orbit of the B system, with its much lower inclination, is *not* co-planar with either of the others; that fact could be seen as a warning that the similarity of the inclinations of the A and AB orbits should be regarded as a mere coincidence.

In summary, we have shown in this paper that HD 30869, an important system in view of its undisputed membership of the Hyades, is a quadruple system. Previously published radial velocities have, with few exceptions, been measured only from the integrated spectrum of the whole system and therefore have, at best, done no more than chart roughly the variations of the brightest component, Aa. From the McDonald spectra, however, we have been able to measure the radial velocities of all four components individually at practically all phases of both the inner orbits and thereby to derive reliable orbital parameters for both sub-systems. At the same time we have made a fresh analysis of the 95-year visual orbit. From spectroscopy and from the orbital parameters we have constructed a model of the system, which (in accordance with the fundamental purpose of this series of papers) can now be considered to be among the best-documented of all the multiple-star systems in the Hyades.

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SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 193: HD 47467, HR 3451, AND HD 223323

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The three objects discussed here are all double-lined F-type stars whose duplicity was initially suspected by Suchkov through the application of his ΔM_{C0} criterion. All three are pairs with accurately equal masses, but except in the case of HD 47467 the component stars are not exactly similar to one another, as they have appreciably different rotational velocities. The periods are 844, 700, and 1175 days, and the orbital eccentricities are 0·51, 0·38, and 0·60, respectively.

Introduction

It has been related previously, notably in Paper 182[1], how Suchkov & McMaster[2] defined a quantity that they called ΔM_{C0} that served as a criterion for what they termed 'over-luminosity' among F-type stars. Quantified in stellar magnitudes, it compared the brightness of a star according to its *Hipparcos* parallax with the brightness that it 'ought' to have according to its Strömgren[3] photometric indices. For nearby single F stars, the two luminosity criteria agreed within $0^{m}\cdot15$ r.m.s., but a goodly number of field stars were found to exhibit discrepancies in the sense that their actual (*Hipparcos*-based) luminosities were too high.

A potent cause of such discrepancies would be duplicity; in the simplest case of two similar stars, the observed luminosity would be doubled while the Strömgren indices would be completely unaffected, so there would be a ΔM_{C0} of $0^{m}\cdot 75$. A discussion[4] of a sample of 111 stars with $\Delta M_{C0} > 0^{m}\cdot 5$, many of which were observed for radial velocity with the Cambridge *Coravel*, showed that at least 64 of them were binaries, although there were also certain seemingly single stars that exhibited anomalous luminosities.

Among the stars that were observed[4] at Cambridge were the three that are discussed in the present paper. They were among the objects for which preliminary orbits were derived, but at the time of publication[4] of those orbits the observations had not been maintained for long enough to provide satisfactory phase coverage; indeed, in the case of HD 223323, the star with the longest period among the three treated here, several different periods covering a range of more than a year were possibilities, although in the event the correct one was selected. *Coravel* observations of the stars have been continued since the publication of the preliminary orbits, which are now to be superseded by the properly documented ones given here.

HD 47467

HD 47467 is a seventh-magnitude star half a degree north-following ψ^3 Aur, or (to put it in a less parochial context) it is halfway between Castor and Capella. As an aside, it is remarked that ψ^3 itself is one of a whole cloud of fifth-magnitude objects that are shown by Bayer[5] in his chart of Auriga as indicating the Charioteer's whip — indeed, in his *Explicatio*[6] he says of them, "*Decem stellulae flagellum constituentes*" — but the letter ψ seems not to be found at all on the actual chart[5], and the superscript numbers seem to have been assigned by Argelander[7]. It may be of interest that there is hope of ψ^6 and possibly also ψ^1 Aur featuring in this series of papers in due course, perhaps around no. 210.

The writer has not been able to find any ground-based *UBV* photometry of HD 47467, so it seems rather surprising that the *Hipparcos* catalogue prefers to quote ground-based values of $V = 7^{m}\cdot 17$, $(B-V) = 0^{m}\cdot 626$ to anything that the satellite measured for itself. It found a parallax of $0''\cdot 01301 \pm 0''\cdot 00120$, leading to a distance modulus of $4^{m}\cdot 43 \pm 0^{m}\cdot 20$ and thus to an absolute magnitude of $+2^{m}\cdot 74$, with the same uncertainty of $\pm 0^{m}\cdot 20$. Suchkov[4] estimated from Strömgren indices an M_V of $+3^{m}\cdot 54$, and so obtained a ΔM_{C0} of $+0^{m}\cdot 80$ which is beautifully explained by the discovery[4] that the spectrum is double-lined, with equal components, so doubling the brightness (a change of 0·75 stellar magnitudes) without in the least affecting the photometric indices. An extraordinary aspect of the *Hipparcos* astrometric results is that they led to an 'acceleration solution', suggesting that there was a continuous acceleration throughout the ~1000-day duration of the observations, whereas not only is the orbital period of 843 days shorter than that duration but in any case the components seem to be very exactly equal, so there ought to be no photocentric motion at all to speak of.

There does not seem to be any MK classification of HD 47467; the *HD* type is F5, but the colour index would be more consonant with G0 V. Despite the brightness of the star, the 'Suchkov paper', as we shall call ref. 4, was the very first one to feature in the *Simbad* bibliography, which includes only two subsequent references. One is to the catalogue of F and G dwarf stars by Nordström *et al.*[8], which includes the information, apparently gleaned from *one* radial-velocity observation, that HD 47467 is a spectroscopic binary with a systemic velocity of 0 ± 5 km s^{-1}.

Simbad perversely notes that value for the radial velocity of the star in preference to the admittedly preliminary γ-velocity of $+1 \cdot 61 \pm 0 \cdot 12$ km s^{-1}, from 10 measurements, given in the Suchkov paper; that paper was itself omitted entirely from the *Simbad* bibliography until a complaint about its absence was made by a third party in 2005. The other paper that refers to the star is concerned with the statistics of *Hipparcos* binaries with non-linear motion, and has little specific application to HD 47467.

HR 3451

HR 3451 is in what the eye sees as a rather blank region of the sky in the south-following part of Lynx, where it makes an equilateral triangle with Pollux and Praesepe. Its *UBV* magnitudes have been given by Oja[9] as $V = 6^{m} \cdot 55$, $(B-V) = 0^{m} \cdot 43$, $(U-B) = 0^{m} \cdot 02$; the *Hipparcos Catalogue* gives $V = 6^{m} \cdot 54$ from *Hipparcos*'s own measurements and $(B-V) = 0^{m} \cdot 469$ from *Tycho*. The *Hipparcos* parallax is $0'' \cdot 01531 \pm 0'' \cdot 00083$. The star features in the *Bright Star Catalogue* only by dint of a little luck, since its V magnitude puts it slightly fainter than the $6^{m} \cdot 50$ ostensible limit of the *Catalogue*. In the *Bright Star Catalogue* itself the V magnitude is entered as "6·33R", where the R means that in the absence (at the time of publication of the *Catalogue*) of any photoelectric measurement, the value that was printed came originally from the *Revised Harvard Photometry*[10] but a correction proposed by Rybka[11] was applied to it. The actual entry in the *Revised Harvard Photometry* is almost the same, $6^{m} \cdot 34$, and stems from three measurements (out of nearly half a million made personally by the Director of the Harvard College Observatory, Pickering[12], in furtherance of the relevant project) obtained in 1896/7 with the 2-inch *Meridian Photometer*[13]. Despite the existence of much more recent and supposedly accurate values, the *Bright Star Catalogue* entry is still being copied into new compilations. For example, in the *ROSAT* survey catalogue of Hünsch, Schmitt & Voges[14], although the distance of the star is obviously from *Hipparcos* the V magnitude is not: it is given as $6^{m} \cdot 33$, and the $(B-V)$ colour (as in many other cases) is given as the improbable $0^{m} \cdot 00$, presumably because there is no entry for it in the *Bright Star Catalogue* and Hünsch *et al.* instructed their computer to interpret a blank as meaning zero. Nordström *et al.*, in their catalogue of F and G dwarfs[8], compounded their poor choice of V magnitude by causing the *Bright Star Catalogue* entry to appear to be extremely accurate by the addition of a zero in the third decimal place to make it $6^{m} \cdot 330$. It is interesting to notice that compilers of modern catalogues seem to prefer observations obtained visually with a two-inch instrument that was constructed in 1878/9 to modern ones made by 'high-tech' means!

The spectral type of HR 3451 was initially given[10] as A, but in the *Henry Draper Catalogue* it is F2. There is one MK classification[15], as F7 V. Apart from that, the principal interest in the star seems to have concerned its rotational velocity. [Olin] Wilson[16] first placed the star in his 'rotation group 1', which by comparison with Slettebak's numerical estimates[17] he deduced to have rotational velocities of 15–25 km s^{-1}. Then Kraft[18] determined rotational velocities for a number of stars; he did not measure HR 3451 for himself but instead quoted Wilson's result, which he telescoped to 20 km s^{-1}. Next, Danziger & Faber[19] took an interest in rotation but did not feel any need to to make their own measurements, since they were able to report mutually corroborative measurements from Wilson *and* Kraft! Comparatively recently, Wolff & Simon[20] determined their own value of $v \sin i$ as 23 km s^{-1}, and Nordström *et al.*[8] found it to be 19 km s^{-1}. In none of the papers was HR 3451 recognized as double-lined, so the rotational velocities are all virtually meaningless; Hünsch *et al.*[14] specifically noted the object as a single star as opposed to being a binary.

There are two publications giving radial velocities of HR 3451. First Harper[21] made measurements on three photographic plates taken with a 1-prism Cassegrain spectrograph giving a reciprocal dispersion of about 30 Å mm^{-1} at Hγ at the Victoria 72-inch reflector; they do not agree well among themselves (range 12·7 km s^{-1}) but their weighted mean is given as +3·0 km s^{-1} with a 'probable error' of 2·2 km s^{-1}. Recently, Nordström *et al.*[8] have given a mean of +0·8 ± 0·5 km s^{-1} from two *Coravel* observations. Even though Nordström *et al.* did not notice the double-lined nature of the spectrum, just as in the case of HD 47467 *Simbad* prefers to quote the radial velocity from those authors rather than from the earlier work[4] of the present writer plus Suchkov, where the preliminary γ-velocity (+2·23 ± 0·31 km s^{-1}) is given in addition to the qualitative fact that the object is a spectroscopic binary.

HD 223323

HD 223323, at seventh magnitude, is to be found within the Square of Pegasus, a little more than one-quarter of the way down a diagonal starting from α Andromedae (the top left-hand star as seen from north-temperate latitudes). The star is of course not bright enough for inclusion in the *Bright Star Catalogue*, but it does feature in the *Supplement*[22]. Its photometry has been given by Guetter[23] as $V = 7^m{\cdot}08$, $(B-V) = 0^m{\cdot}41$, $(U-B) = -0^m{\cdot}12$; Oja[24] obtained $7^m{\cdot}07$, $0^m{\cdot}42$, $-0^m{\cdot}08$ for the corresponding quantities. *Hipparcos* found $V = 7^m{\cdot}08$; the *Tycho* $(B-V)$ is $0^m{\cdot}443$. The only MK type reported by *Simbad* for HD 223323 is Harlan's[25] F2 IV–V, but there is also a classification of F3 IV by Grenier *et al.*[26]. Normally, $(U-B)$ colour indices barely reach into negative values where they pass through a minimum in the early F types; the surprisingly negative index of HD 223323 reflects not only the fact that the star is of a considerably earlier integrated type than the other two that are considered here but also indicates a substantial metal-deficiency. That was in fact recognized in the spectral type suggested on the basis of Vilnius[27] photometry (not, therefore, a true spectroscopic classification) by Bartevičius and Lazauskaitė[28], who put the type at 'MD-F4 V'. A deficiency of [Fe/H] = −0·61 was proposed in the Suchkov paper[4] on the basis of Strömgren indices, while on a similar footing Nordström *et al.*[8] gave it as −0·60. The same attributes that conspire to make the star so bright in the ultraviolet also weaken the spectral lines and thereby make HD 223323 quite a difficult object to measure with the *Coravel*.

There have been several measurements of the radial velocity of HD 223323 in addition to those made by the writer. Abt & Willmarth[29] published five velocities obtained at Kitt Peak with CCDs at the coudé spectrograph of the 84-inch reflector, but with the use of the 38-inch coudé feed telescope and not the 84-inch itself. They discovered the binary nature of the object in 1988 at the very first observation, in which it was seen double-lined, and they confirmed that result by repeating the observation on the next night. Three further spectra obtained in subsequent observing runs, however, showed only single lines. Fehrenbach *et al.*[30] obtained four measurements by their objective-prism method; they agree unusually well with one another, yielding a mean of +11 ± 0·4 km s^{-1} (whose small formal uncertainty is clearly misleading, since on that basis the actual error is about fifty standard deviations!), but of course could not be expected to contribute to any orbital solution. Grenier *et al.*[26], who took three photographic spectra at 80 Å mm^{-1} with the 1·52-m telescope at Haute-Provence, saw the spectrum only as single-lined, and in any case they did not offer the results of individual spectra but only the mean, of $-8 \cdot 3 \pm 1 \cdot 5$ km s^{-1}.

New radial velocities and orbits

In late 1999 there appeared the paper by Suchkov & McMaster[2] that suggested the existence, among the bright F stars observed by *Hipparcos,* of a lot of hitherto unrecognized double-lined binary (hereinafter SB2) systems. Since they had escaped direct resolution by *Hipparcos,* they would have to have angular separations of no more than the order of $0'' \cdot 1$, and at the typical distances of 7^m F dwarfs they would therefore have linear separations of at most a few AU and periods of at most a few years. Since they thereby promised to constitute, if indeed Suchkov & McMaster were correct, a large pool of 'new' and potentially important SB2 objects, the present author enquired of Suchkov if he were following up the prediction with an actual observing campaign and, on learning that he was *not*, the author offered to undertake one himself with the Cambridge *Coravel.* That was what led to the 'Suchkov paper'[4], which did indeed demonstrate the SB2 nature of a substantial proportion (though not by any means all) of the stars that were flagged by Suchkov & McMaster's ΔM_{C0} criterion.

The observing campaign, on about 80 previously unobserved stars, began early in 2000, and the observations on each star started as soon as it became accessible in the sky. After about two years the work was written up; orbits were given where possible for the newly discovered binaries, but they were not the principal focus of the paper, and of the 28 orbits about half had to be regarded as preliminary owing to major deficiencies in the phase distributions and/or overall duration of the observations. The three stars treated in the present paper are cases in point.

HD 47467 is one of the reddest and latest-type stars on the Suchkov programme, and therefore gives one of the largest 'dip' areas in terms of the total of the two dips. Of course SB2s have the total area split between the two dips, often far from equally, and are therefore much more difficult to measure than single-lined systems, especially in respect of a weak secondary. HD 47467 is, for an SB2, a particularly favourable case: it gives two dips that are so similar to one another as to be mutually indistinguishable. Although the dips are almost unbroadened by rotation (or other mechanisms), the radial-velocity amplitudes are fairly small and even at the more favourable node the pair is never more than just separated (Fig. 1). Whereas in the original write-up[4] the orbit depended upon only ten SB2 measurements, of which nine were all within a stretch of two-fifths of the orbital cycle, there are now 52 SB2 observations (plus five, reduced as single-lined, made when the components had almost identical velocities), and the phase coverage is satisfactory.

The general procedures for handling SB2 radial-velocity traces (whose 'unscrambling' was first demonstrated[31], in this *Magazine*, on Palomar traces 25 years ago) have long been established. In cases where the two dips are tolerably distinct from one another (meaning* $\Delta V > \sim 15$ km s^{-1} in the case of HD 47467, although no hard-and-fast convention is adopted) the traces are reduced with all parameters (two dip positions, two depths, two rotational velocities, and the continuum level) free to take their optimal values. Where the dips are substan-

*We use V to mean radial velocity here — not to be confused with visual magnitude.

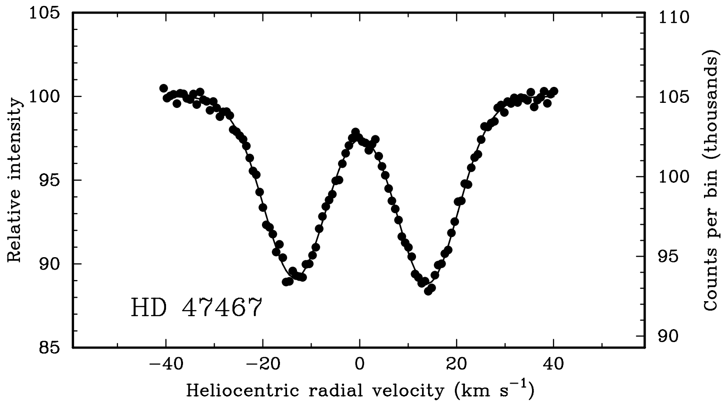

FIG. 1

Radial-velocity trace of HD 47467, obtained with the Cambridge *Coravel* on 2003 December 8 and showing the twin dips at nearly their maximum separation.

tially or wholly blended together (and for HD 47467 they appear absolutely single-lined for $\Delta V < \sim 10$ km s^{-1}) the dip profiles (widths and relative areas) are imposed on the solution, the imposed parameters being mean values from the independently reduced traces. For those cases, therefore, the only unknowns for which the traces are solved are the dip positions (plus the continuum level). In the last resort, when $\Delta V \sim 0$, the traces are reduced as if they were single-lined, and the resulting radial velocity is listed mid-way between the columns giving the velocities of the primary and secondary in journals of observations (Table I for HD 47467) and are not used in the derivation of the orbital elements. Not surprisingly, twin velocities deduced from traces in which the components are very heavily blended together tend to be less reliable than others; it has been found empirically that for HD 47467 it is appropriate to attribute a weighting of $^1/_3$ to traces that can be reduced as SB2 but have $\Delta V < 5$ km s^{-1}. The orbital solution made on that basis is plotted in Fig. 2; the elements are presented, with those of the other stars discussed below, in Table IV towards the end of this paper.

It should be mentioned that all the velocities in this paper have been left 'as determined' by the Cambridge *Coravel*; experience suggests, however, that to make them consonant with the zero-point generally adopted in this series of papers they probably need a correction of about $-0 \cdot 5$ km s^{-1}, perhaps as much as $-0 \cdot 8$ km s^{-1} for HD 223323. In any case, as has been made very clear previously[32], such validity as the formal precisions of the listed γ-velocities may have are only internal to the respective data sets concerned and are often far smaller than the true uncertainties of the radial velocities of the centres of mass of the systems concerned.

The character of the spectrum of HR 3451 is peculiarly ill-adapted to radial-velocity measurement, being double-lined but showing substantial rotational broadening of the lines of both components. The projected rotational velocities (16 and 24 km s^{-1}) are both greater than the radial-velocity amplitudes, with the result that the two dips seen in *Coravel* traces are never separated; in fact the system appears single-lined most of the time. A particularly good trace obtained close to the phase of maximum velocity separation, at the orbital node that occurs very

TABLE I

Radial-velocity observations of HD 47467

All observations were made with the Cambridge Coravel

Heliocentric Date	*HMJD*	*Velocity* Prim. km s⁻¹	*Velocity* Sec. km s⁻¹	*Phase*	*(O − C)* Prim. km s⁻¹	*(O − C)* Sec. km s⁻¹
2000 Feb. 22·03	51596·03	+9·0	−5·3	0·340	+0·5	0·0
Oct. 9·22	826·22	+1·8		·613	—	—
Nov. 17·18	865·18	+0·5*	+2·3*	·659	+0·4	−0·9
20·14	868·14	−0·3*	+4·0*	·662	−0·3	+0·7
30·17	878·17	+1·8		·674	—	—
Dec. 22·10	900·10	−0·6*	+4·2*	·700	+0·8	−0·5
2001 Jan. 7·08	51916·08	−2·1	+5·5	0·719	0·0	+0·1
Feb. 13·96	953·96	−4·2	+7·3	·764	−0·1	−0·1
Mar. 10·99	978·99	−5·5	+9·3	·794	0·0	+0·4
Apr. 28·85	52027·85	−8·7	+12·4	·852	+0·2	+0·1
Aug. 21·13	142·13	−10·9	+13·9	·987	0·0	−0·4
Oct. 4·19	186·19	+1·7		1·039	—	—
10·16	192·16	+1·6		·046	—	—
Nov. 1·13	214·13	+7·5	−3·9	·072	+0·3	+0·1
14·22	227·22	+8·4	−6·0	·088	−0·3	−0·6
26·10	239·10	+9·8	−5·7	·102	+0·2	+0·6
Dec. 12·13	255·13	+10·4	−7·0	·121	+0·1	+0·1
2002 Jan. 1·07	52275·07	+11·1	−7·2	1·145	+0·3	+0·4
Feb. 6·05	311·05	+10·9	−8·1	·187	0·0	−0·4
Mar. 7·94	340·94	+10·1	−7·7	·223	−0·5	−0·4
Apr. 4·87	368·87	+10·0	−7·2	·256	−0·1	−0·4
Sept. 28·20	545·20	+5·6	−2·1	·465	−0·1	+0·3
Oct. 18·21	565·21	+5·2	−1·8	·489	+0·1	0·0
Dec. 5·11	613·11	+3·8*	−0·2*	·545	+0·2	+0·1
2003 Jan. 5·12	52644·12	+2·4*	+0·8*	1·582	−0 2	+0·1
Feb. 15·02	685·02	+1·7		·631	—	—
Mar. 14·93	712·93	−0·1*	+3·4*	·664	−0·1	+0·1
Apr. 7·90	736·90	−0·6*	+3·5*	·692	+0·5	−0·9
May 7·87	766·87	−2·7	+5·6	·728	−0·2	−0·2
Sept. 29·20	911·20	−12·3	+15·3	·899	−0·2	−0·1
Oct. 25·21	937·21	−13·8	+17·3	·930	0·0	+0·1
Nov. 28·12	971·12	−13·6	+17·3	·970	−0·2	+0·6
Dec. 8·09	981·09	−12·0	+15·2	·982	−0·1	−0·1
12·04	985·04	−11·0	+14·1	·986	+0·1	−0·4
15·15	988·15	−10·2	+13·7	·990	+0·2	0·0
27·12	53000·12	−6·7	+11·3	2·004	+0·4	+0·9
29·05	002·05	−6·5	+10·0	·006	0·0	+0·2
2004 Jan. 9·07	53013·07	−3·1	+6·6	2·020	−0·1	+0·3
15·07	019·07	−0·9	+5·0	·027	+0·3	+0·5
26·03	030·03	+2·6*	+1·1*	·040	+0·7	−0·3
Feb. 8·98	043·98	+5·2	−1·6	·056	+0·2	+0·2
22·92	057·92	+7·7	−3·9	·073	+0·4	+0·1
Mar. 1·00	065·00	+7·7	−4·9	·081	−0·4	−0·1
29·92	093·92	+9·9	−7·3	·115	−0·3	−0·4
Apr. 21·89	116·89	+10·6	−7·7	·143	−0·2	−0·2
Sept. 21·16	269·16	+8·3	−5·7	·323	−0·5	−0·1
Oct. 26·21	304·21	+8·1	−4·5	·365	+0·1	+0·2
Dec. 18·12	357·12	+6·6	−3·2	·427	0·0	+0·1

TABLE I (*concluded*)

Heliocentric Date	*HMJD*	*Velocity* Prim. km s⁻¹	Sec. km s⁻¹	*Phase*	*(O − C)* Prim. km s⁻¹	Sec. km s⁻¹
2005 Jan. 4·99	53374·99	+6·2	−2·8	2·449	+0·1	0·0
Mar. 18·91	447·91	+3·6*	−0·4*	·535	−0·3	+0·2
Oct. 10·21	653·21	−4·5	+8·8	·778	+0·3	+0·7
Nov. 4·18	678·18	−6·7	+9·3	·808	−0·4	−0·3
25·12	699·12	−7·8	+11·0	·833	−0·1	−0·1
2006 Jan. 29·01	53764·01	−13·1	+15·9	2·910	−0·3	−0·2
Mar. 1·98	795·98	−14·3	+17·2	·948	0·0	−0·4
Apr. 3·92	828·92	−10·9	+14·0	·987	+0·1	−0·4
May 11·87	866·87	−0·6*	+3·0*	3·032	−0·7	−0·2

*Velocities derived from close blends; weighted 1/3 in orbital solution.

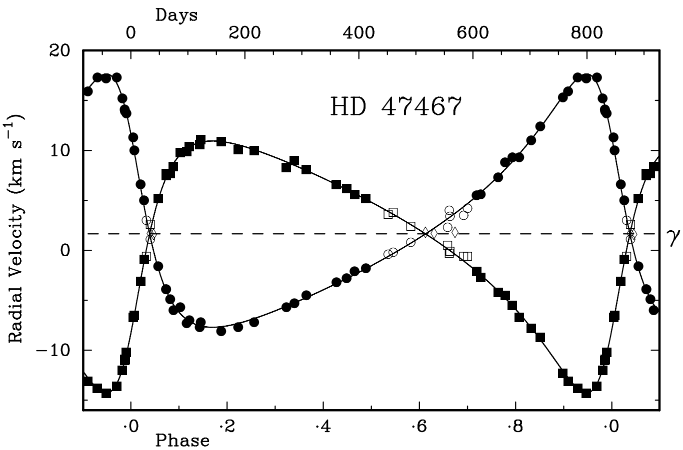

FIG. 2

The observed radial velocities of HD 47467 plotted as a function of phase, with the velocity curves corresponding to the adopted orbital elements drawn through them. Radial velocities of the primary star are plotted as squares, those of the secondary as circles. The open symbols are used in cases where the twin velocities have been unravelled from close blends ($\Delta V \leqslant 5$ km s^{-1}); they have been attributed a weighting of 1/3 in the orbital solution. A few measurements plotted as open diamonds have been reduced as single-lined and not used in the solution at all.

nearly at periastron passage, appears here as Fig. 3. It will be apparent from the scale of ordinates that the zero level (as in Figs. 1 and 5) is very heavily suppressed (the zero line would come more than a whole page-height below the bottom of the page) and the dips are actually very shallow. Even at the best phase, the two dips are seen to be badly blended together, and despite a good integration to get the *S/N* ratio seen in Fig. 3 there remains some uncertainty as to just how the blend should be assigned between the individual components. It is of interest that the radial-velocity traces of HR 3451, and in particular the line-widths, are remarkably similar to those of HD 193468, treated and illustrated in a recent paper[33] in this series; the measurements of the traces of HR 3451 are, however, much less

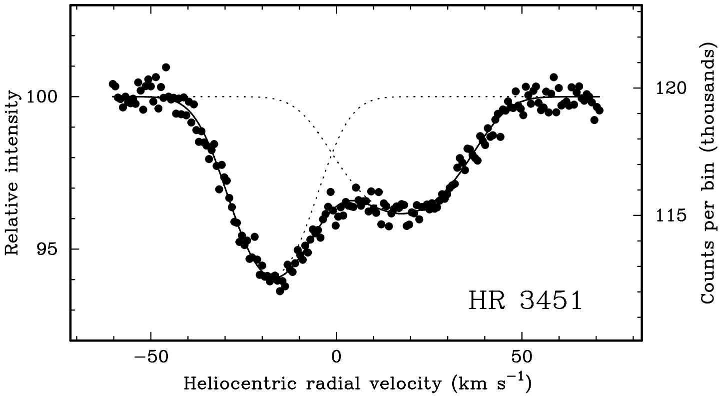

FIG. 3

Radial-velocity trace of HR 3451, obtained with the Cambridge *Coravel* on 2004 April 16 and showing the twin dips at nearly their maximum separation.

reliable than those of the *HD* star, because the latter has radial-velocity amplitudes that are twice as great as those of HR 3451, so at favourable phases the dips are almost entirely separated and their profiles can be determined accurately.

At the conclusion of the observing campaign on HR 3451, it has been considered best to make fresh reductions of all the observations, uniformly imposing the best dip parameters, which have been estimated by averaging the results from all the traces obtained in the vicinity of the node and initially reduced with all parameters 'free'. The velocities so obtained are listed in Table II. Two traces that were made at times when the velocities of the components were almost identical were reduced as single-lined. The three velocities published by Harper[21] are inserted at the head of the table.

There are some bad residuals, but in view of the difficulties presented by HR 3451 they are not to be wondered at. They are particularly frequent where the velocity separation is very small; on that account the seven traces which have yielded velocity separations < 5 km s^{-1} have been half-weighted. To equalize the variances of the two components, the velocities of the secondary (the one giving the wider and shallower dip) had to be given a global weighting of $^1/_4$. The worst

TABLE II

Radial-velocity observations of HR 3451

Except as noted, all observations were made with the Cambridge Coravel

Heliocentric Date	*HMJD*	*Velocity*		*Phase*	*(O−C)*	
		Prim. *km s^{-1}*	*Sec.* *km s^{-1}*		*Prim.* *km s^{-1}*	*Sec.* *km s^{-1}*
1924 Mar. 15·31*	23859·31	+2·2		$\overline{39}$·264	—	—
1926 Apr. 13·25*	24618·25	+0·2		$\overline{38}$·348	—	—
1931 Apr. 18·23*	26449·23	+12·9		$\overline{36}$·962	—	—

TABLE II (*concluded*)

Heliocentric Date	*HMJD*	*Velocity* Prim. km s⁻¹	*Velocity* Sec. km s⁻¹	*Phase*	*(O−C)* Prim. km s⁻¹	*(O−C)* Sec. km s⁻¹
2000 Feb. 20·04	51594·04	−0·8†	+2·9†	0·867	+1·4	−2·0
Apr. 26·95	660·95	−13·4	+19·4	·962	+0·9	+2·8
29·95	663·95	−15·3	+18·4	·966	−0·5	+1·3
Nov. 13·23	861·23	+3·2†	+0·8†	1·248	−0·7	+1·7
2001 Jan. 14·11	51923·11	+7·2	−2·0	1·336	0·0	+2·2
Feb. 17·03	957·03	+8·0	−3·2	·385	−0·4	+2·1
Mar. 13·97	981·97	+9·4	−6·2	·420	+0·4	−0·3
Apr. 28·90	52027·90	+8·7	−6·5	·486	−0·9	0·0
Nov. 3·22	216·22	+5·0	−1·8	·755	−0·7	+0·9
14·24	227·24	+3·0†	+1·6†	·771	−2·0	+3·6
Dec. 6·17	249·17	+2·2		·802	—	—
12·19	255·19	+1·3		·811	—	—
20·14	263·14	+1·8†	+1·0†	·822	0·0	−0·1
30·12	273·12	+1·4†	+3·7†	·836	+0·7	+1·5
2002 Jan. 18·06	52292·06	−0·9	+4·7	1·863	+1·0	+0·1
25·10	299·10	−2·9	+9·0	·873	0·0	+3·4
Feb. 4·09	309·09	−2·8	+6·5	·888	+1·8	−0·7
14·04	319·04	−6·7	+11·6	·902	−0·4	+2·7
23·00	328·00	−7·9	+12·7	·915	+0·1	+2·1
Mar. 8·01	341·01	−11·8	+12·4	·933	−1·2	−0·6
26·94	359·94	−14·9	+15·8	·960	−0·8	−0·6
Apr. 4·90	368·90	−15·5	+18·1	·973	−0·1	+0·4
19·87	383·87	−17·0	+18·9	·994	−0·2	−0·2
26·90	390·90	−17·1	+19·3	2·004	−0·1	0·0
May 22·88	416·88	−16·1	+17·4	·041	−0·8	−0·2
Oct. 4·21	551·21	+3·0†	−0·7†	·233	−0·1	−0·5
Dec. 5·18	613·18	+6·3	−2·7	·322	−0·5	+1·1
2003 Jan. 7·15	52646·15	+9·2	−4·1	2·369	+1·2	+0·9
Feb. 19·01	689·01	+9·2	−4·9	·430	+0·1	+1·1
Mar. 17·87	715·87	+8·1	−4·6	·468	−1·4	+1·8
23·93	721·93	+9·3	−6·5	·477	−0·3	−0·1
May 13·90	772·90	+9·8	−7·4	·550	+0·1	−0·8
Nov. 28·20	971·20	+0·4†	+2·1†	·833	−0·5	+0·2
2004 Mar. 1·02	53065·02	−14·4	+17·0	2·967	+0·4	−0·2
17·03	081·03	−16·8	+17·4	·990	−0·2	−1·5
29·96	093·96	−16·2	+18·6	3·008	+0·8	−0·7
30·94	094·94	−16·5	+19·7	·010	+0·5	+0·4
Apr. 11·92	106·92	−15·8	+19·9	·027	+0·6	+1·2
16·93	111·93	−16·2	+18·8	·034	−0·3	+0·6
May 10·87	135·87	−13·9	+10·5‡	·068	−1·4	−4·4
21·90	146·90	−10·9	+12·1	·084	−0·4	−0·9
Dec. 27·13	366·13	+9·1	−4·3	·397	+0·5	+1·2
2005 Jan. 26·11	53396·11	+9·3	−4·4	3·440	+0·1	+1·7
Mar. 25·00	454·00	+9·7	−7·3	·522	0·0	−0·7
May 2·89	492·89	+9·2	−7·0	·578	−0·4	−0·5
30·89	520·89	+8·4	−8·1	·618	−0·8	−2·0
Dec. 18·18	722·18	−7·6	+10·9	·905	−0·8	+1·5
2006 Feb. 16·97	53782·97	−16·7	+17·2	3·992	0·0	−1·8
Apr. 3·94	828·94	−13·4	+16·9	4·058	+0·3	+0·9
10·97	835·97	−13·3	+14·2	·068	−0·8	−0·7
May 18·89	873·89	−5·7	+8·5	·122	+0·3	−0·1

*Photographic measurement by Harper[21]; not used in orbital solution.
†Velocities derived from close blends; weighted 1/2.
‡Rejected measurement.

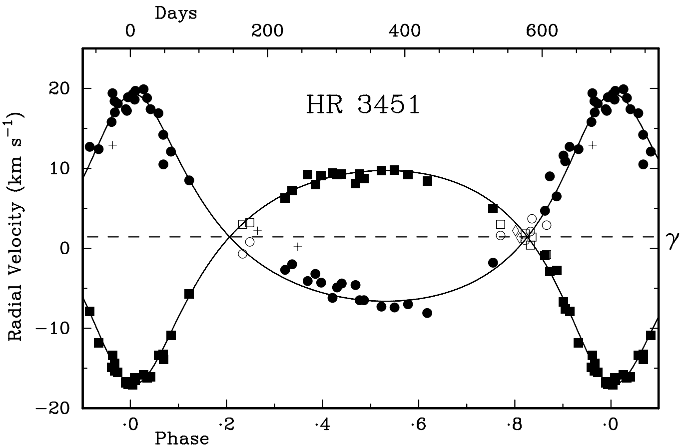

FIG. 4

The observed radial velocities of HR 3451 plotted as a function of phase, with the velocity curves corresponding to the adopted orbital elements drawn through them. The meanings of the symbols are exactly the same as in Fig. 2, except that in the present case the open squares and circles indicate *half*-weighted velocities. The plusses represent the three photographic observations made long ago by Harper[21]; they were not taken into account in the orbital solution.

residual of all arises from a trace that appears to be corrupted in the region of the secondary dip; the corresponding measurement has been rejected. The finally derived orbit is illustrated in Fig. 4 and its elements will be found in Table IV below.

For HD 223323, the preliminary orbit proposed in the Suchkov paper[4] was more preliminary than most, because the observations covered less than two-fifths of a complete cycle. By good fortune, however, that part of the cycle included the periastron passage and both nodes of an orbit that was obviously of high eccentricity. The unobserved section of the orbit clearly consisted of a long interval of slow change, but the actual length of that interval was very uncertain. A clue was available in the form of the observations made in 1988–1990 by Abt & Willmarth[29], especially the two double-lined ones (which effectively constituted only one observation, as they were made on successive nights); the velocities showed that the system was near a nodal passage then, but *which* node, and on which side of it, was not certainly determinable. The small differences between the single-lined measurements, however, did tend to favour one particular choice for the phase and cycle count of the double-lined ones, and on that basis a period (carefully hedged with *caveats*) of about 1189 days was adopted from among a number of possibilities ranging up to 1580 days. It proves to have been the correct choice, the period found now being 1175 days with an uncertainty not much above one day.

The velocity amplitudes of HD 223323 are large enough in relation to the widths of the dips that the latter are seen completely resolved in traces obtained near the nodes of the orbit, *cf.* Fig. 5. The mean observed widths of the dips correspond to $v \sin i$ values of 6 km s^{-1} for the primary and 11 km s^{-1} for the secondary, with a ratio of areas of 1 to 0·9. Those parameters were imposed upon the reductions of the more heavily blended traces. There are 59 double-lined Cambridge observations, plus one single-lined one; they are set out in Table III, with the velocities given by Abt & Willmarth[29] at its head. We follow here the expedient adopted in

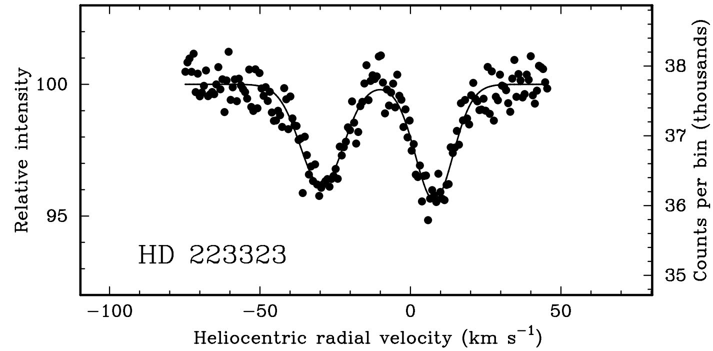

FIG. 5

Radial-velocity trace of HD 223323, obtained with the Cambridge *Coravel* on 2004 June 8 and showing the twin dips at nearly their maximum separation.

the Suchkov paper[4] of attributing half-weight to the first eight pairs of Cambridge velocities, for no better reason than that they were made — as was recognized retrospectively — unnecessarily close together in time and might give undue weight to a small interval of phase. The data and the velocity curves are drawn in Fig. 6; the orbital elements, together with those of the other two stars discussed here, appear in Table IV.

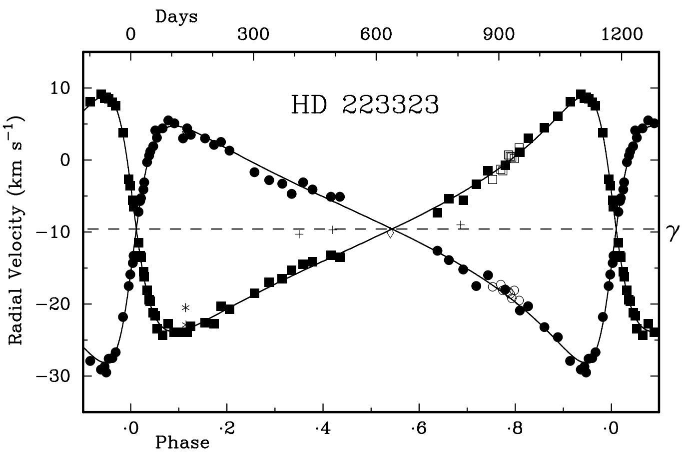

FIG. 6

The observed radial velocities of HD 223323 plotted as a function of phase, with the velocity curves corresponding to the adopted orbital elements drawn through them. The meanings of the symbols are exactly the same as in Fig. 2, except that in the present case the open squares and circles indicate *half*-weighted velocities. The asterisks represent the two double-lined observations made by Abt & Willmarth[29] (they are hidden by other symbols in the case of the secondary star); the plusses represent the single-lined measurements published by the same authors, none of whose velocities was utilized in the solution of the orbit.

TABLE III

Radial-velocity observations of HD 223323

Except as noted, all observations were made with the Cambridge Coravel

Heliocentric Date	*HMJD*	*Velocity* Prim. km s⁻¹	*Velocity* Sec. km s⁻¹	*Phase*	*(O – C)* Prim. km s⁻¹	*(O – C)* Sec. km s⁻¹
1988 Nov. 23·19★	47488·19	−20·5	+3·7	$\bar{3}$·114	+3·0	−0·7
24·17★	489·17	−22·9	+3·5	·115	+0·6	−0·9
1989 Aug. 28·42★	47766·42	−10·3		$\bar{3}$·351	—	—
Nov. 18·26★	848·26	−9·7		·420	—	—
1990 Sept. 27·37★	48161·37	−9·0		$\bar{3}$·687	—	—
2000 Aug. 9·11	51765·11	−2·6†	−17·3†	0·753	−0·8	+0·1
29·08	785·08	−0·5†	−16·9†	·770	+0·5	+1·3
Sept. 3·14	790·14	−0·5†	−17·6†	·775	+0·2	+0·8
17·05	804·05	+1·0†	−17·9†	·787	+1·1	+1·1
21·03	808·03	+0·6†	−18·3†	·790	+0·6	+0·9
25·09	812·09	+0·3†	−19·2†	·793	+0·1	+0·1
Oct. 1·01	818·01	+0·1†	−18·2†	·798	−0·4	+1·4
13·00	830·00	+1·7†	−19·5†	·809	+0·7	+0·6
Nov. 3·96	851·96	+3·0	−20·3	·827	+0·9	+0·9
Dec. 13·86	891·86	+4·5	−23·2	·861	+0·3	+0·1
2001 Jan. 15·77	51924·77	+6·1	−24·6	0·889	0·0	+0·6
Feb. 14·78	954·78	+8·1	−27·9	·915	+0·3	−1·0
June 25·07	52085·07	−15·5	−4·1	1·026	+0·5	−1·0
July 24·11	114·11	−21·6	+4·1	·050	+0·2	+1·4
28·12	118·12	−23·4	+3·1	·054	−1·2	0·0
Aug. 11·09	132·09	−24·3	+4·4	·066	−1·1	+0·3
25·07	146·07	−22·7	+5·5	·078	+1·0	+0·9
Sept. 29·98	181·98	−23·9	+3·0	·108	−0·2	−1·6
Oct. 10·01	192·01	−23·9	+4·4	·117	−0·4	0·0
18·98	200·98	−23·1	+3·5	·124	+0·2	−0·7
Nov. 22·89	235·89	−22·6	+3·0	·154	−0·3	−0·2
Dec. 14·87	257·87	−22·7	+2·1	·173	−1·0	−0·5
31·83	274·83	−20·3	+2·5	·187	+0·8	+0·5
2002 Jan. 21·79	52295·79	−20·7	+1·3	1·205	−0·2	−0·1
May 31·09	425·09	−16·5	−3·3	·315	+0·2	−0·9
June 23·06	448·06	−15·3	−4·7	·335	+0·8	−1·7
July 21·11	476·11	−14·5	−3·1	·358	+0·8	+0·7
Aug. 13·09	499·09	−14·1	−4·1	·378	+0·6	+0·3
Sept. 27·05	544·05	−13·2	−5·1	·416	+0·3	+0·5
Oct. 19·01	566·01	−13·5	−5·1	·435	−0·6	+1·1
2003 Feb. 19·76	52689·76	−10·1		1·540	—	—
June 15·09	805·09	−7·3	−12·6	·638	−0·9	+0·1
July 13·09	833·09	−5·4	−13·9	·662	+0·1	−0·3
Aug. 17·11	868·11	−5·6	−15·2	·692	−1·2	−0·4
Sept. 18·05	900·05	−3·4	−17·5	·719	−0·1	−1·6
Oct. 16·98	928·98	−1·5	−16·0	·744	+0·7	+0·9
Nov. 27·89	970·89	−0·7	−18·0	·779	−0·2	+0·6
2004 Jan. 2·81	53006·81	+1·1	−20·9	1·810	0·0	−0·7
May 31·09	156·09	+9·1	−29·1	·937	+0·3	−1·2
June 8·97	164·97	+8·6	−28·7	·945	−0·3	−0·6
13·08	169·08	+8·7	−29·5	·948	−0·2	−1·5
19·08	175·08	+8·5	−27·6	·953	−0·3	+0·3
28·09	184·09	+8·0	−27·5	·961	−0·2	−0·1

TABLE III (*concluded*)

Heliocentric Date	*HMJD*	*Velocity* Prim. km s⁻¹	Sec. km s⁻¹	*Phase*	*(O − C)* Prim. km s⁻¹	Sec. km s⁻¹
2004 July 6·09	53192·09	+7·5	−26·7	1·968	+0·1	−0·2
24·07	210·07	+3·8	−21·8	·983	+0·3	+0·9
Aug. 7·12	224·12	−2·7	−17·5	·995	−1·2	+0·1
11·06	228·06	−3·6	−15·9	·998	−0·5	+0·1
17·11	234·11	−5·6	−14·3	2·003	+0·2	−0·9
19·07	236·07	−6·5	−13·3	·005	+0·1	−0·8
31·04	248·04	−11·5	−7·2	·015	+0·2	+0·2
Sept. 4·08	252·08	−13·3	−5·7	·019	−0·1	+0·2
6·07	254·07	−13·5	−5·3	·020	+0·4	−0·1
14·05	262·05	−16·2	−3·1	·027	+0·3	−0·5
21·03	269·03	−18·1	−0·3	·033	+0·3	+0·5
26·02	274·02	−19·4	+0·6	·037	0·0	+0·3
29·08	277·08	−19·6	+1·2	·040	+0·4	+0·3
Oct. 6·04	284·04	−21·2	+1·9	·046	0·0	−0·1
Nov. 26·87	335·87	−23·9	+5·1	·090	−0·1	+0·4
2005 June 11·08	53532·08	−18·5	−1·7	2·257	+0·2	−1·3
July 17·11	568·11	−17·0	−2·8	·288	+0·6	−1·3

*CCD measurement by Abt & Willmarth[29]; not used in orbital solution.
†Weighted 1/2 in orbital solution — see text.

TABLE IV

Orbital elements for HD 47467, HR 3451, and HD 223323

Element	*HD 47467*	*HR 3451*	*HD 223323*
P (days)	843·6 ± 0·5	700·3 ± 1·0	1175·1 ± 1·3
T (MJD)	52996·6 ± 0·7	52387·8 ± 2·7	53230·0 ± 0·9
γ (km s^{-1})	+1·65 ± 0·03	+1·43 ± 0·11	−9·56 ± 0·06
K_1 (km s^{-1})	12·60 ± 0·08	13·39 ± 0·14	16·38 ± 0·11
K_2 (km s^{-1})	12·68 ± 0·08	12·97 ± 0·25	16·40 ± 0·16
q $(=m_1/m_2)$	1·006 ± 0·009	0·968 ± 0·021	1·001 ± 0·012
e	0·5109 ± 0·0029	0·381 ± 0·010	0·604 ± 0·003
ω (degrees)	239·1 ± 0·5	174·5 ± 2·1	77·8 ± 0·6
$a_1 \sin i$ (Gm)	125·7 ± 0·8	119·2 ± 1·3	211·1 ± 1·6
$a_2 \sin i$ (Gm)	126·4 ± 0·8	115·4 ± 2·3	211·3 ± 2·2
$f(m_1)$ $(M_\odot)$	0·1114 ± 0·0022	0·138 ± 0·005	0·272 ± 0·006
$f(m_2)$ $(M_\odot)$	0·1133 ± 0·0022	0·125 ± 0·008	0·273 ± 0·008
$m_1 \sin^3 i$ $(M_\odot)$	0·451 ± 0·007	0·518 ± 0·024	1·091 ± 0·027
$m_2 \sin^3 i$ $(M_\odot)$	0·448 ± 0·007	0·535 ± 0·017	1·089 ± 0·023
R.m.s. residual (wt. 1) (km s^{-1})	0·34	0·68	0·53

Discussion

HD 47467 is revealed as a double star whose components are of extraordinary equality. The dips in radial-velocity traces, and equivalently the luminosities of the stars, are indistinguishable from one another, and the mass ratio is unity to well within its standard deviation of less than 1%. The masses, $0{\cdot}45/\sin^3 i\ M_\odot$, suggest that $\sin^3 i \sim 0{\cdot}4$, so $\sin i \sim 0{\cdot}73$, $i \sim 47°$. Using the value just estimated for $\sin i$, we find the major axis of the relative orbit, $a_1 + a_2$, to be about 2·3 AU, which in angular terms would equate to 2·3 times the parallax or about $0''{\cdot}03$, so the system could be expected to be almost beyond resolution by speckle interferometry with a single telescope but a good candidate for separated-aperture interferometers.

The orbit of HR 3451 given here is a great improvement over the preliminary version pubished in the Suchkov paper[4]. The standard deviation of the period, in particular, has dropped from 75 days to 1. Yet there is no cause for complacency, since the nature of the radial-velocity traces still leaves appreciable uncertainty in the adopted rotational velocities, and that uncertainty feeds through into the relative areas of the two dips and thereby into the magnitude difference Δm between the components. *Prima facie*, there are inconsistencies between the various parameters that bear on Δm. Fig. 3 definitely suggests that the left-hand dip is the one that belongs to the primary star (primary in the sense of being the more luminous one), because its area appears to be greater than that of the other; its substantially greater depth more than makes up for its smaller width, although not by a large margin — the adopted ratio of dip areas is 1 to 0·9. The normal interpretation, on the basis of both stars being on the main sequence, as is largely confirmed by the *Hipparcos* parallax, would be that that component (the one with the deeper dip) has a luminosity a tenth of a magnitude or so brighter than its companion. It is therefore disconcerting to see that the orbital elements give its mass as being smaller than that of its companion (by 3·2 ± 2·1 per cent — so not by a tremendously significant amount). Furthermore, the stars are in that region of the main sequence where the typically rapid rotations of the early-type stars are giving place to the modest velocities of the later-type ones, and it would be natural to expect that the larger rotational velocity would belong to the star of earlier type, *i.e.*, the one which we would expect to be the primary. Again, the fact as given here is the reverse of expectation.

It is proper to point out that the true uncertainty in the q value (the mass ratio) from the orbital elements is larger than the 2·1% given in Table IV, which is only a formal uncertainty derived from the respective components' radial-velocity amplitudes. Those amplitudes are susceptible to significant systematic error arising from the procedure used to obtain the velocities upon which they are based. It may be appreciated by reference to Fig. 3 that if the right-hand dip (the broad secondary component) were assigned a smaller width than is portrayed, the right-hand side of its profile would still have to match the right-hand side of the observed trace, so its centre would have to move to the right. Thus, since all traces were reduced with standard dip profiles imposed on them, by adopting a smaller rotational velocity we would drive the velocities of the secondary further from the γ-velocity in every trace, thereby increasing the velocity amplitude found for that star. To fit the traces there would have to be a corresponding *in*crease in the rotational velocity ascribed to the primary, resulting in an apparent *de*crease in the velocity amplitude of that component. The combined effect would be an increase of q, possibly to more than unity, which might seem agreeable, although at the same time the Δm judged from the relative dip areas would increase, making the disparity of luminosities greater and thereby tending to exacerbate the original difficulty. It is not immediately clear whether the nett effect would be an increase or decrease in embarrassment. The writer refrained from undertaking specific experiments to ascertain the sign and magnitude of the effect because he preferred not to know. It seemed best in terms of scientific integrity to base judgements of dip widths solely on the traces that show the dips and not on how the outcome of those judgements might impinge upon prejudices arising from external considerations, so ignorance seemed an ideal protection from (even unconscious) bias.

The true masses of the stars that constitute HR 3451 might be estimated at about $1 \cdot 4\ M_{\odot}$, so those given by the orbit imply that $\sin^3 i \sim 0 \cdot 38$, $\sin i \sim 0 \cdot 72$, $i \sim 46°$, practically the same as the case of HD 47467. Then the major axis of the relative orbit is about $2 \cdot 2$ AU, which at the *Hipparcos* distance subtends an angle of a little over $0'' \cdot 03$ — again, very similar to HD 47467. The ΔM_{C0} value[4] for HR 3451 is $0^{m} \cdot 54$, not much above the lower limit imposed in the selection of stars for the Suchkov programme; it is fully explained — rather more than fully, in fact — by the approximate doubling of the luminosity by the duplicity of the star.

The phase distribution of the measurements of HD 223323 is now satisfactory and the period is perfectly secure and determined with considerable accuracy. As in the case of HR 3451, it is a bit disconcerting that the apparent secondary (the star that gives the slightly smaller dip in radial-velocity traces) has a larger rotational velocity than the primary, but the difference between the stars is very slight and the mass ratio is very exactly unity. If the spectral types are considered to be quite early in class F, the masses may be near $1 \cdot 5\ M_{\odot}$, so the values of $1 \cdot 09/\sin^3 i$ given by the orbit imply $\sin^3 i \sim 0 \cdot 72$, $\sin i \sim 0 \cdot 90$, $i \sim 63°$. The major axis of the orbit is about $3 \cdot 2$ AU, so at the parallax of $0'' \cdot 015$ it could be expected to subtend nearly $0'' \cdot 05$; the system is therefore potentially resolvable by speckle interferometry when well away from periastron. Just as in the cases of HD 47467 and HR 3451, the Suchkov ΔM_{C0} value, in this case $0^{m} \cdot 66$, is entirely cleared up by the duplicity of the star. There is no doubt that in all three cases treated in this paper, the ΔM_{C0} parameter has operated perfectly as a criterion of duplicity, and when the duplicity is taken into account the remaining discrepancies are easily consonant with the dispersion of $0^{m} \cdot 15$ found by Suchkov & McMaster[2] for their sample of nearby single F stars.

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REVIEWS

Meteorites and the Early Solar System II, edited by Dante S. Lauretta & Harry Y. McSween, Jr. (University of Arizona Press, Tucson), 2006. Pp. 943, 28·5 × 22 cm. Price $90 (about £50) (hardbound; ISBN 0 816 52562 5).

Meteorites are gifts from space, randomly delivered and randomly selected, and then dropped rather precipitously onto the surface of our planet for us to find, collect, curate, and study in laboratories. They present us with conveniently fragmented, handy-sized examples of inner-Solar-System worlds. Some of the meteorite parent bodies were Mars-sized and had differentiated. The subsequent fragmentation that led to the depletion and spreading of the asteroid belt has thus provided meteorite scientists with examples of 'planetary' inner cores, mantles, and crusts. As such, meteorites are the answers to a rock collector's prayer. Other parent bodies were much smaller and thus unheated and unaltered. Their meteoritic fragments are reminiscent of the original elemental and molecular mixture that permeated the inner regions of the pre-planetary nebula at the dawn of the Solar System.

Meteoritics is a relatively new subject. Prior to the 19th Century the idea of *le vide planétaire* was paramount. Interplanetary and interstellar space was void, except maybe for "some very thin vapours, steams or effluvia arising from the atmospheres of the Earth, planets, and comets". Any rocks falling from the sky were thought to be either volcanic ejecta or earthy accumulations fused by thunder and lightning. But the distinctive and unusual composition of meteorites, and the witnessing of falls such as Siena (1794), Wold Cottage (1795), and L'Aigle (1803), changed the scientific conception.

By 2006 enough was known to enthuse 88 authors to generate a total of 943 pages of review articles with relative ease. The resultant volume reveals not only how much our views have changed since the early 1800s, but also how they have changed considerably since the first *Meteorites and the Early Solar System* in this Arizona Space Science Series, published in 1988. Astrophysicists now realize that chondritic meteorites provide some of our best clues to the end-point of nuclear synthesis, and to the 'metallic' elemental composition of the solar photosphere. It is also realized that meteorites take us even further back in time than Sun-birth. The primitive meteorites contain dust grains that come from the outer atmospheres of earlier stars. So not only are meteorites a vital clue to the conditions that prevailed when the planets were formed, they also contain information about the triggers that induced star and planet formation in the first place.

Meteoritics is not an 'easy' subject, simply because modern laboratory technology has enabled us to learn so much. But in this comprehensive and thorough book, the authors of the reviews have made special efforts to link the different aspects of this wide-reaching and fascinating subject and in doing so have provided the intended graduate audience with an accessible, well referenced, and beautifully illustrated text, and a book to be proud of.

The whole space-science and planetary community owe a huge debt of gratitude to the Lunar and Planetary Laboratory and the University of Arizona Press for producing a volume such as this. — David W. Hughes.

Joint Evolution of Black Holes and Galaxies, edited by M. Colpi, V. Gorini, F. Haardt & U. Moschella (Taylor & Francis, New York), 2006. Pp. 459, 24 × 16·5 cm. Price £85/$149·95 (hardbound; ISBN 0 750 30999 7).

Over the last decade, one of the most important advances in observational cosmology has been the discovery of the symbiotic relationship between super-massive black holes and galaxies. In particular, the discovery of tight correlations between black-hole mass and galaxy mass in the local Universe has led to the realization that the formation and evolution of super-massive black holes and massive galaxies must be intimately connected. Consequently, the last few years have seen a large number of conferences and meetings devoted to the subject of the joint evolution of galaxies, black holes, and quasars. Although usually informative, the written proceedings of these meetings are often hampered by the need to include write-ups of a large number of contributed talks, each of which can only be allocated a small number of pages.

Within this context, *Joint Evolution of Black Holes and Galaxies*, which brings together the contents of a doctoral school held in Como, Italy, in 2003, is greatly superior compared with standard conference proceedings. The structure of the book is well organized into eight chapters that review our current knowledge in various aspects of the field. Each of the chapters is approximately 50 pages in length and, as a result, the authors are afforded the opportunity to discuss important background information, as well as the current state of the art in their separate, but related, fields of research.

The book begins with an in-depth review of the observational evidence for the existence of super-massive black holes in the centres of local galaxies, and the various observational tracers of the underlying correlation between black-hole and galaxy stellar mass. This successfully sets the scene for later chapters that include discussions of our current knowledge of active galactic nuclei (AGN), structure formation within the current cold-dark-matter paradigm, and the formation of the first primordial objects at extreme redshift. Although each of the chapters is well written and informative, a particular highlight is a comprehensive review of the successes — and failures — of current models of galaxy formation.

Due to the nature of the subject, there is a significant amount of overlap in the material described in several of the chapters. However, I personally see this as an advantage, given that it can often be enlightening to read several different explanations of the same subject, each highlighting different aspects. In conclusion, the *Joint Evolution of Black Holes and Galaxies* successfully covers most of the important areas of this extremely active field of research, and in significantly more detail than a standard conference proceedings. Consequently, I imagine that it will be of great interest to both professional astronomy researchers and post-graduate students alike. — Ross McLure.

Scientific Requirements for Extremely Large Telescopes (IAU Symposium 232), edited by P. A. Whitelock, M. Dennefeld & B. Leibundgut (Cambridge University Press), 2006. Pp. 517, 25·5 × 18 cm. Price £60/$100 (hardbound; ISBN 0 521 85608 6).

Some conference proceedings are harder to review than others. This, covering the 2005 November meeting in Cape Town, is one of those, since it could equally well be described as 'a compact summary of the state of the art of ground-based optical and infrared astronomy, astrophysics, instrument and telescope technologies, and of current plans for progress'! Simply having got an approximation to this definition into 517 pages, albeit of fairly fine print, is a tribute to the industry of the editors, and, since they achieved the published version in a mere eight months after the conference itself took place, to their ruthlessness.

Such speed and such density of information are achieved with penalties. There are moderately numerous typos, though few are seriously irritating (most are simple spelling mistakes), while here and there the text would have benefitted from editing for clarity. The figures, however, do not generally measure up to the quality of the textual material, for the most part because they have been made so small that reading their annotations often requires a hand lens. Those in science papers are generally better (the Figures 1 of the papers by Eline Tolstoy and by Chris Evans *et al.* are models of clarity), but even there, some figures are intrinsically unclear at varying levels. Fig. 1 of Dietrich Baade *et al.* is clear enough, though irritatingly pixellated, but their Fig. 2 is both distorted (stretched horizontally) and fuzzy to a level which makes it downright unpleasant to look at (though it remains reasonably intelligible). One or two figures are quite *un*intelligible, however: for example, Fig. 4 of Cuby *et al.*, a casualty of grey-scale reproduction. The poor quality of the figures was about the only aspect of the production of the book that I found significantly disappointing. However, since most are taken from other publications, better (= larger) versions are doubtless out there to be 'Googled' if need be.

Overall these proceedings are an impressive indication of the thought and work now being devoted to the development of the science case, technology, and instrument concepts for this daunting new generation of ground-based telescopes. I counted 89 contributions. Overviews and general scene-settings by Phil Charles, Dave Buckley *et al.*, and Malcolm Longair, *inter alia*, are followed by technical reviews. Those on the status of detector technology, by Klaus Hodapp and Don Hall, and on adaptive optics (AO) for ELTs, by Norbert Hubin, Brent Ellerbroek, and 12 collaborators in this field, are truly excellent and offer invaluable (though necessarily dense) summaries of the *status quo* and prospects in these critical areas.

The integration of science and technology is dealt with rather well in several papers. For example, the general AO article by Hubin *et al.* is nicely complemented by a study by Benoit Neichel and nine collaborators of a specific science requirement which shows that primordial (-ish) galaxies will be best studied if at least 40% of incident light from a 30+-m telescope can be concentrated onto a 25- or 50-μm-square pixel. Achieving this seems most likely through multi-object adaptive optics (MOAO), a potentially critical technique for achieving substantial improvements in image quality, and hence high ensquared* energy values, on sets of objects scattered over several arcminutes of sky. MOAO has not, thus far, been demonstrated on a telescope, though laboratory work seems promising. Neichel *et al.* point out an important "gain with increasing aperture" — we need all of

*Energy falling within a square [pixel] area, *cf.* 'encircled' energy; a useful neologism in AO studies!

those that nature offers — whereby the need for *natural* (as opposed to *laser*) guide stars to correct tip-tilt effects (image movement) decreases when the telescope diameter approaches the largest ('outer') scale length of the atmospheric turbulence, since the average slope of the wavefront over the aperture must then approach zero. Another, but unmentioned, 'gain' is the increase with aperture of the tip-tilt isoplanatic angle ($\theta_{\rm iso} \sim D_{\rm tel}$/[layer altitude]), as this determines the field in which we must find our natural guide stars if the correction is to be useful: the bigger $\theta_{\rm iso}$, the more stars are likely to be available.

Amongst several 'ELTs in the context of other facilities' papers, that on the *SKA* by Steve Rawlings is unfortunately present in abstract only (victim, no doubt, of the editors' ruthless speedy-publication policy). Jonathan Gardner (*JWST*) and Thomas Wiklind (*ALMA*, *Herschel*) valiantly attempt to describe the numerous synergies between the sprawling science cases of these future facilities and the vast range of ELT science. However, setting out such interfaces properly (*i.e.*, in a fashion genuinely useful to us lesser mortals who are neither familiar with the details of all the other developments nor blessed with eidetic memory) calls for a meeting on a scale similar to that of this symposium: one which, in my opinion, should be seriously and urgently considered. In this symposium, 'synergies' would probably have been more usefully addressed towards the end, when the reader/participant has had a chance to understand the breadth of the scientific potential of the ELTs.

There follows an impressive series of ~10-page overviews of major science fields, covering galaxy formation and cosmology by Patrick McCarthy, the intergalactic medium by Raghunathan Srianand, stellar populations by Rosie Wyse & Gerry Gilmore, and exoplanets by Karl Stapelfeldt. The review from which I personally learned most was that by Srianand, probably because of my relative ignorance of a field which is clearly advancing extremely rapidly and on which ELTs will evidently have a major impact. Indeed, Srianand's endorsements could usefully, and accurately, have gone beyond a timid 'ELTs can contribute' towards a more robust 'ELTs will enable dramatic advances' in this field.

The symposium continued with no less than four parallel science sessions on the above topics, at which 40 oral papers (published length ~5 pages) and 11 posters (~2 pages) were presented. A 5th (!) parallel session outlined the diversity of ELT projects worldwide. A large fraction of the science papers are highly complementary to the broader plenary reviews, providing current results on, for example, H_2 in the IGM (Srianand, again) amidst numerous topics. I was impressed by the simple *chutzpah* of the *CODEX* team, who propose (*inter alia*) the direct measurement of cosmic acceleration by high-S/N absorption-line spectroscopy of high-redshift sources with a precision *and stability* of ~5 mm s^{-1} y^{-1}, a mere two orders of magnitude better than the current state of the art. (However, having seen that state evolve through about the same range during my own career, I shall not be surprised, if spared, to see this optimism vindicated.) Of particular (and slightly sad) resonance for me was Eline Tolstoy's discussion of why we *really* need to be able to do photometry of main-sequence-turnoff stars in the Virgo cluster if we are truly to understand the formation processes of galaxies, especially early types, in the full range of environments. The sadness arises because it is apparent from her analysis that we will not achieve this until we have at least a 100-m telescope in space, which will *not* be in my lifetime!

The final plenary sessions covered the status of the various ELT projects, summaries of the parallel sessions, 'general' topics not easily shoe-horned into the parallel sessions (such as ingenious proposals for the exploitation of quantum optical effects), and an invaluable technology-*cum*-systems-approach overview by Colin Cunningham and Dave Crampton, which makes the slightly startling, but sensible, suggestion that an internationally co-ordinated and co-operatively produced suite of several specialized ELTs might be more cost effective and scientifically productive than an equal number of basically similar general-purpose telescopes each produced by, and serving, different regional astronomical communities. Those contributing to these proceedings include China, Europe, Japan, more than one North American group, and Russia (though from the abstract which made it into press, Russia seems more likely to choose to be a collaborator than an instigator).

In summary, these proceedings are of a generally high standard and offer an exceptionally useful summary of the technical and scientific status of the world's ELT projects. I worked in this area for half a decade, but have certainly learned a great deal from reviewing this volume, and am certain to learn more. Were I still professionally involved I would not hesitate to lay out the necessary cash to acquire these proceedings, even if I was quite sure that I would not be able to claim it back from the operation! I would recommend the volume, also, to those in need of a compact overview of much of current astrophysics, with the limited caveat that it naturally concentrates on the optical-IR wavebands of direct relevance to a ground-based telescope (though the 'synergy' sections fill some of the resulting gaps). Indeed, it is a volume worth possessing if one is involved, or just interested, in the next stage of the development of astronomy from planet Earth. — TIM HAWARDEN.

Astronomical Polarimetry: Current Status and Future Directions (ASP Conference Series, Vol. 343), edited by A. Adamson, C. Aspin, C. J. Davis & T. Fujiyoshi (Astronomical Society of the Pacific, San Francisco), 2006. Pp. 530, 23·5 × 15·5 cm. Price \$77 (about £44) (hardbound; ISBN 1 583 81210 5).

It is 200 years since the concepts related to the polarization of radiation emerged within the scientific community and 60 years since polarimetry became a diagnostic tool for exploring stellar phenomena and the interstellar medium. The previous and only international conference simply embracing astrophysical polarimetry was in Tucson, Arizona, just over 30 years ago[1]. Did we need another? The papers presented in Hawaii in 2004 clearly provide an emphatic "Yes". The importance of polarimetry as a means to understanding the nature and behaviour of planets, stars, the interstellar medium, galaxies, quasars, and the cosmic microwave background is clearly demonstrated by the number of researchers actively engaged in it. The conference coverage was admittedly not completely comprehensive, concentrating on the optical–infrared–millimetre spectral domains — UV, X-ray, and γ-ray polarimetrists were absent. Coverage according to types of astrophysical source is virtually complete, although solar topics were dealt with by a single short review paper; polarimetry of the Sun now warrants individual conferences with their own published proceedings[2].

In the standard form of the ASP Conference Series, the presented papers (~ 105) are organized in six sections covering (*i*) instrumentation and data analysis, (*ii*) molecular clouds, star formation, Solar System and extrasolar planets, (*iii*) circumstellar matter and ejecta, (*iv*) interstellar medium, (*v*) stars, and (*vi*) extragalactic astronomy and cosmology. No individual paper or single topic stands out as giving a 'buzz' to the proceedings. I feel that very few of the papers will have future citations, but the tome offers a good impression of the number of research groups who now include polarimetry in their armoury as a matter of course. What is refreshing is the absence of the need of any presenter first to provide a lesson on what Stokes parameters represent. In that regard polarimetry has truly 'come of age'. It may be noted that several instrumental and theory articles cover the possible detection of extrasolar planets by polarimetry. Discovery of such objects by such means is keenly awaited! — DAVID CLARKE.

References

(1) T. Gehrels (ed.), *Planets, Stars and Nebulae Studied with Polarimetry* (University of Arizona Press, Tucson), 1974.
(2) D. Clarke, *The Observatory*, **124**, 399, 2004.

Annual Review of Astronomy and Astrophysics, Volume 44, 2006, edited by R. Blandford, J. Kormendy & E. van Dishoeck (Annual Reviews, Palo Alto), 2006. Pp. 580, 24 × 19·5 cm. Price $196 to institutions (about £103), $85 to individuals (about £45) (hardbound; ISBN 0 824 30944 8).

The lead article in the latest volume of this well-respected series, entitled 'An engineer becomes an astronomer', is a fascinating insight into the early days of radio astronomy in Australia by one of the pioneers, Bernard Mills, and is well worth reading for the candour with which the growth of the subject, in a country which has played a major rôle in the discipline, is described. Thereafter, we are treated to 11 substantial reviews in which stellar themes predominate.

But to start at the beginning (or at least fairly close to it), we find a study by Xiaohui Fan *et al.*, of the observational constraints available to pinpoint the epoch of re-ionization; present data suggest it to have been a drawn-out process between a z of around 14 down to perhaps 6. Then, given the stuff with which to form stars, we can appreciate the attempt to classify diffuse and molecular clouds by Snow & McCall and can get up to date on the complex chemistry found in space. And once star (and planet) formation gets under way, we'll need *Spitzer* to see what's going on; Werner *et al.* share with us the first fruits of that mission (which, encouragingly, looks likely to last until 2009).

Turning to the other end of the spectrum, we have three papers reporting on results from observations in X-rays. Fabbiano describes the populations of X-ray binaries in galaxies out to 30 Mpc discovered principally by *Chandra* and *XMM-Newton* (why not just plain *Newton*?), while Remillard & McLintock discuss the properties of that subset of 20 sources that contain a 'dynamically-confirmed black hole'. (I look forward to further confirmation *via* gravitational-wave detectors!) Not unrelated to such studies is the (multi-wavelength) review by Gaensler & Slane of pulsar-wind nebulae, which may give rise to even higher-energy (TeV) emission. On a grander scale, X-ray emission from extragalactic jets and its relationship to the radio picture is considered by Harris & Krawczynski.

Back to 'bread-and-butter' astronomy, I was delighted to find a modern review of the absolute-magnitude calibrations of various 'standard-candle' variable stars by those 'fathers' of the subject, Sandage & Tammann; alarmingly, the calibrations for Galactic and Magellanic Cloud Population I Cepheids show zero-point and slope differences which can have an impact further afield. And further afield is where we find Renzini investigating what can be discerned from the stellar populations of elliptical galaxies about the evolution of those systems. In a similar vein, Brodie & Strader look at the implications for formation and evolution of galaxies in the light of the metallicity of their globular clusters. And finally, Woosley & Bloom examine the connection between core-collapse supernovae and γ-ray bursters; who knows, maybe here we have another standard candle awaiting calibration.

So, astronomically, we have a fine collection of benchmark reviews, but I cannot let the publishers get away without some admonition. While the general quality of the production has improved steadily over the years and colour now features widely in the articles, until Volume 43 the series sat well on my shelf as a set. No more! Most pages now sport a useless 5·4-cm-wide margin, which means that the width of the book is now fully 3·5 cm wider than previously and sticks out on the shelf accordingly; assuming, of course, that it will fit on the shelf at all: the new volume is also 0·5 cm taller than the last one (which in turn was 0·5 cm taller than Volume 36). Equally annoying is the fact that the layout of lettering on the spine has changed, and the familiar black box, which once contained the title of the publication, has now slipped down to the lower part of the spine. One has the impression that we should consider this the start of a new series and find a new location in the library for it! It wasn't bust so why fix it? — DAVID STICKLAND.

Europe's Quest for the Universe, by L. Woltjer (EDP Sciences, Les Ulis, France), 2006. Pp. 323, 24 × 16 cm. Price €35 (about £24) (paperback; ISBN 2 868 83813 8).

As a former Director General of ESO and past Chairman of ESA's Space Science Advisory Committee, Lo Woltjer brings a wealth of experience to this review of European ground- and space-astronomy programmes. Although the coverage is comprehensive I found the content a bit variable and the structure lacking some coherence.

When Woltjer describes the founding of ESO and the development of the ESO 3·6-m, the *NTT*, and the *VLT* he tells an interesting story and shows how some of the critical decisions about the telescopes and of the location of the ESO headquarters were made. As someone who knows little of ESO's early history I found this very interesting, although I was rather frustrated by incidents (and personalities) that are obviously known to insiders but are not explicitly described. To give one example, who was it who joined the *VLT* project then left after nine months and whose contribution appears to be only the addition of 'much additional bureaucracy'? In contrast a number of other personalities who apparently had a positive impact are named, but the reader learns little about them. Where did they come from? What did they do apart from the little nugget of ESO work described here? It is a shame that the reader does not come away with more of a feel for those personalities.

When moving on to ESA, the feel of the author's personal touch on the tiller starts to fade. The descriptions of missions and results is fairly complete, if necessarily superficial, but there are some failures of structure here. Terms, concepts, or mission acronyms are sometimes introduced without explanation only to be clarified later in the chapter. If you work in the field these things will be familiar, but if you are reading this as a member of the 'educated public' you would have to have been quite well educated to know some of these details. Towards the end of the book are sections on 'Publications' and 'Researchers and funding'. These are certainly innovative and thought provoking, but it's not clear to me if the quoted level of detail is helpful. The proportion of national spending on astronomy is interesting, as are publication statistics, but combining these to produce histograms of 'Astronomy pages published per inhabitant per EU country' might be taking it a bit too far. So, on balance this is a book with some interesting chapters and one in which the author's opinions come over very clearly. His description of the rôle of the ESA facility ESRIN as "variable and not always clear, except that politically it had to be continued in Italy" hints at some attitudes and behind-the-scenes dealing to which, once again, the reader is not privy. — JOHN DAVIES.

New Atlas of the Moon, by Thierry Legault & Serge Brunier (Firefly Books, Richmond Hill, Ontario), 2006. Pp. 128, 36·5 × 29 cm. Price £35 (hardbound; ISBN 1 554 07173 9).

This splendid new lunar atlas (actually an English translation from the French original of 2004) will be of interest to observers both new and old. Its large format is put to very good use with a series of fine full-disc CCD images of the Moon at different phases. Some images are provided with an acetate overlay with selected marked features. Each page highlights what may be especially interesting to view at that particular phase, and also gives some special sidelight on a lunar feature, historical anecdote, or spacecraft mission. Boxes on each double-page spread nicely show the appearance of the Moon with binoculars and the naked eye to compare with the large south-at-top telescopic image: an image showing the E–W inverted view is also included. Following the full-disc image section there is a large selection of lunar close-ups (some showing the effect of differing illumination) with potted geological histories of each feature. The images beautifully show the lunar rilles (including the observationally challenging Alpine Valley) in exceptional detail and clarity; as a practical observer, this was a highlight of the book for me. Details of eclipses, practical observing hints, and timetables of lunar phases, eclipses, and co-longitudes till 2011 complete the work. The authors illustrate just how critical the question of collimation is in securing the highest possible resolution, and the tips on photography, imaging, and compositing will be very useful to disciples of this field.

All the high-resolution images reproduced are the work of the renowned French lunar photographer — and nowadays CCD imager — Thierry Legault, using an aperture of only 30 cm. The text is co-authored by fellow countryman Serge Brunier, a well-known author and popularizer. (Twenty years ago atop Pic du Midi, Brunier joined Jean Dragesco and me to photograph the Moon and planets with the observatory's 1-metre Cassegrain: no webcams then!)

This atlas will inevitably be compared with works in print such as the (revised) Hatfield lunar atlas and Rükl's lunar atlas and charts. Hatfield's has more detailed line diagrams, and Rükl's has many short biographical details of those after whom lunar features have been named. All these works really complement one another, so the new atlas will be worth getting even if you already have others. For those with older works from the 1960s to 80s, say, Legault's imaging far outstrips the *Times* or the Kuiper lunar atlas in terms of resolution (though perhaps not in terms of weight!), but the latter contain close-ups under different conditions of illumination. Of the works by traditional lunar photographers, the atlas by Georges Viscardy remains the most detailed.

Serious observers of the Moon will regret that the authors have not published the date and time of each high-resolution image, so that others would be enabled to make precise comparisons under identical conditions of illumination. It is also a pity that the binding for the book interrupts and slightly spoils the fine image adorning the cover.

In summary, this is a very fine atlas and deserves attention by school and college libraries, public observatories, and serious lunar observers. — RICHARD MCKIM.

Planetary Rings, by Larry W. Esposito (Cambridge University Press), 2006. Pp. 202, 25·5 × 18 cm. Price £60/$110 (hardbound; ISBN 0 521 36222 9).

"How do you know?", was a question frequently posed by the famous astronomical polymath Sir William H. McCrea. I wish Larry Esposito had been asked this question, and that he had been encouraged to answer it a few times in *Planetary Rings*. Far too many of his statements magically pop out of a hat rather like the conjuror's rabbit.

Take mass. We are told that the rings of Saturn have the same mass as its moon Mimas. The readers then have to jump up and find a text book that tells them that this is about $3 \cdot 7 \times 10^{19}$ kg. But in *Planetary Rings* there is no explanation as to why this value has been chosen. Take composition. We are told that the ring particles have a similar composition to nearby moons. But later on in the book, in the case of Saturn's ring particles, we are informed that they are 90–99% water. Now I can understand how multi-frequency space-probe spectroscopy could detect that the ring particles were covered with a rough frost, but how do they know what is inside the particles? Then we are informed that the particles are slow spinning, temporary, low-density (less than 1000 kg m^{-3}) rubble piles. You have guessed it: supporting evidence is absent for all these assertions.

Where do the rings come from? All we are given are vague hints about past collisions, episodic mass injections, and youthfulness. But rather like a lady's age, durations and specific numbers are not mentioned. Where do the rings go to when their life is over? Here I was rather surprised that more was not made of the possibility that the 20-kilometre-high mountainous ridge around Iapetus was formed by a collapsing primordial ring. For other rings we are left to imagine a meteoric endpoint in the gas-giant atmosphere.

I found this book disappointing. I was left with no clear impression of the intended readership. But if it was a PhD thesis the examiners would have a field day. — DAVID W. HUGHES.

Space-Time, Relativity, and Cosmology, by J. Wudka (Cambridge University Press), 2006. Pp. 320, 25·5 × 18 cm. Price £30/$55 (hardbound; ISBN 0 521 82280 7).

In presenting *Space-Time, Relativity, and Cosmology*, Jose Wudka provides a highly readable account of the development of scientific ideas of space and time, culminating with the development of relativity and our modern understanding of the relativistic Universe.

Intended for educated non-scientists, this edition covers a broad sweep of material from creation myths to modern cosmology. In some ways, however, this broad approach, with its laudable aim of providing a history of scientific ideas, creates a certain imbalance in the text. Early chapters, dealing with the scientific method and the development of scientific thought from the Greeks to the Middle Ages, may fail to connect with a certain fraction of readers. In contrast to this, there is a slightly rushed feel to the later chapters on Special and General Relativity, where more text and figures could be spent helping the reader through such topics as the Michelson–Morley experiment and the rejection of the ether, and especially in order to illustrate further the background and solution of the various special relativistic 'paradoxes'. Future editions would do well to revisit these areas.

There are many aspects that will satisfy the reader: the cartoon-style (yet still informative) figures bring freshness to the material and the chapter on the relativistic Universe explains many aspects of modern research in a clear and entertaining manner. This book will certainly appeal to course instructors introducing relativity and cosmology to non-science students and the non-quantitative, accessible account will surely sit well with students. — JON WILLIS.

Wonders of the Planets, by R. Prinja (Mitchell Beazley, London), 2006. Pp. 192, 27 × 25 cm. Price £20 (hardbound; ISBN 1 845 33244 X).

Few subjects appeal to the visual senses more than planetary exploration, humanity's remarkable endeavour to understand the nature of the worlds that populate the Solar System. Today, courtesy of an armada of automated spacecraft, everyone from a young child to a senior citizen can stare in wonder at images showing the strange landscapes of Mars, the turbulent cloud formations of Jupiter, and the magnificent rings of Saturn. Not surprisingly, the visual impact of this book is one of its major attractions. The author, an astrophysicist at University College London, has assembled an impressive selection of more than 100 images, nearly all in full colour, sent back by robotic ambassadors from Earth. These, alone, take up half of the book.

In a departure from the usual planet-by-planet approach, Prinja has decided to adopt a thematic approach, with an emphasis on comparative planetology. After a brief introduction, which touches on the origins of the Solar System and the golden age of planetary exploration, the author launches into a wide-ranging chapter entitled 'Hurricanes and storms'. In some seven full pages of text, he goes on to summarize current ideas and discoveries about subjects ranging from hurricanes on Earth, the Great Red Spot, dust storms and devils on Mars, the atmosphere of Venus, coronal mass ejections, and aurorae on various planets. A similar methodology is used in subsequent chapters about volcanoes, impacts and craters, the search for life, planetary rings, and extrasolar planets. This approach is fine, as long as the reader does not expect to gain much in-depth understanding of each theme or each planet.

As a visually impressive coffee-table volume, this book is one of the best I have seen for some time. The text is also quite informative, wide-ranging, and up-to-date. The only major anomaly I spotted was a description of NASA's *JIMO* mission, which was cancelled in 2005. As the author rightly points out, "We are today in the midst of a period of truly unprecedented discovery and exploration of the Solar System". For anyone who has yet to appreciate the achievements of this new golden age of exploration, this book provides an eye-catching introduction. — PETER BOND.

The Ideas of Particle Physics: An Introduction for Scientists, 3rd Edition, by G. D. Coughlan, J. E. Dodd & B. M. Gripaios (Cambridge University Press), 2006. Pp. 254, 24·5 × 19 cm. Price £30/$50 (paperback; ISBN 0 521 67775 0).

Particle physics is the study of the interactions between fundamental forces and fundamental particles. We understand the forces. We've measured the properties of the particles. Aren't we about finished? *The Ideas of Particle Physics* does a lovely job of disabusing us of that notion, whilst opening up the richness and diversity within this ostensibly esoteric branch of physics, making its intricacies accessible to a non-specialist readership.

The overall structure of the book is loosely chronological, with much of it devoted to following the development of particle physics from the excitement and confusion following the first discoveries of radioactivity, through the changes inflicted upon our understanding of kinematics by the theory of Special Relativity and the profound philosophical shifts wrought in our understanding of the behaviour of micro-objects by quantum mechanics, to the latest refinements of the Standard Model.

People familiar with the second edition (1991) should note that the last decade has provided stunning new data from particle-physics experiments, and many of the results are included in the later chapters of this newest edition: measurements of CP violation in the kaon and B-meson sectors have provided insights into the observed matter/antimatter asymmetry in the Universe (Chapters 39 and 45); results from the *SNO* experiment indicate that neutrinos change flavour as they travel from the Sun to the Earth (Chapter 41); the *LEP* collider has stopped running with an emotional bang after allowing physicists to catch (maybe!) a glimpse of the elusive Higgs particle, leaving an incredible legacy of high-precision measurements (Chapters 38 and 40). In addition, the *LHC* is due to start running in 2007, with the expectation that there the Higgs particle will be found, or not (Chapter 40).

And then the book moves on to what we don't know — 96% of our Universe. The ties between particle physics and cosmology are shown to be ever more insistent as we attempt to understand the Universe at different scales. The theories intertwine and wrap back on themselves, like the very strings, branes, and compactified dimensions to which we are introduced in the final chapters.

Astronomers who want to expand their understanding of the theory, structure, and terminology of particle physics in order better to appreciate the intersection between this field and their own would find this book to be an excellent beginning. I will be recommending this book as extra reading to my 2nd-year undergraduate students in their introductory course on particles and nuclei, although my personal bias is against introducing students to particle physics *via* the historical route in which they have to share in the temporary confusions of past generations who didn't have the luxury of knowing about the quark model!

As a particle physicist, I greatly enjoyed reading the book and refreshing my memory of the various theoretical principles and ideas, as well as recent experimental results. Mathematics is not ignored, but is kept to a minimum, and anyone with a scientific training beyond A-level will have the tools they require to understand and enjoy the vast majority of the concepts and insights presented. On a note of caution, there are some small typographical errors, such as on page 148 where it is incorrectly stated that 'qq' is a colour singlet, but such slips are only occasionally distracting. — LAURA KORMOS.

Brave New Universe: Illuminating the Darkest Secrets of the Cosmos, by P. Halpern & P. Wesson (Joseph Henry Press, Washington, DC), 2006. Pp. 264, 23 × 16 cm. Price £16·99/$27·95 (hardbound; ISBN 0 309 10137 9).

I have to confess that my usual holiday reading is something along the lines of the adventures of Sir Harry Flashman, although I have been known to enjoy a bit of science fiction or fantasy from time to time. Perhaps that latter interest is what kept me turning the pages of *Brave New Universe* — a well-written and very user-friendly guide to the plethora of post-Einsteinian theories and speculations on the nature of the Universe — while recently disporting myself on a sun-lounger on Aphrodite's isle.

Being an inveterate sceptic with a Newtonian disposition, I never really took easily to relativity, but I have to admit that some practical demonstrations, such as gravitational lensing, are rather hard to dispute, given the spectacular images of Einstein rings taken with the *Hubble Space Telescope* and other modern instruments. Not that that would ever inhibit me from putting up stiff resistance to Higgs bosons, dark energy, and 'branes', to name but a few outrageous modern notions. Nonetheless, such things are 'all the go' in astronomy, and, as my mother-in-law once remarked, it would be better to be dead than out of fashion. So I thought I should take the plunge and a peek into this *Brave New Universe*.

Halpern & Wesson trip lightly through the developments of 20th-Century cosmology from the resolution of Olbers' paradox through to the current quests for dark matter and dark energy, and on to all manner of proposals — often bizarre — for the true nature of the Universe, taking in the necessary elements of particle physics and some mathematical concepts (I thought I'd dispensed with tensors after my BSc!) on the way. Many of the leading players in this 'game' are shown in cameo, giving the story a human dimension, and a wealth of humble analogies are drawn to keep the man on the Clapham omnibus on board, but all without recourse to the vulgar intrusion of actual mathematics.

I must say I found it all quite captivating (not that I would ever admit to believing a word of it!) and I would thoroughly recommend it to anyone feeling left behind by the astronomical 'thundering herd' of the 21st Century. If nothing else, the vocabulary of modern astro-particle cosmology is introduced in a more palatable form than one could ever get from a simple dictionary, giving readers ample opportunity to impress their friends and relations. — DAVID STICKLAND.

An Introduction to Optical Stellar Interferometry, by A. Labeyrie, S. G. Lipson & P. Nisenson (Cambridge University Press), 2006. Pp. 325, 25·5 × 18 cm. Price £45/$80 (hardbound; ISBN 0 521 82872 4).

The growing impact of interferometric methods in optical and near-infrared astrophysics — close to 100 papers either utilizing or discussing these methods will have appeared in the refereed literature in 2006 alone — has created a need for a text that introduces these new tools to advanced undergraduate and graduate students. *An Introduction to Stellar Interferometry* aims to fill this gap by bringing together three experts who have made contributions to the field over many years. The fruit of their labour, a volume containing over 300 pages, is wide ranging, covering both qualitative and quantitative introductions to interferometry and aperture synthesis at optical wavelengths, as well as expositions of parallel areas of interest such as the effects of atmospheric turbulence on optical imaging and optical/infrared interferometric methods using filled-aperture telescopes.

Understandably, in attempting to cover such a broad remit, the authors have had to balance detail *versus* scope. In some instances their choice is spot-on, *e.g.*, the chapters on the 'Optical effects of the atmosphere' and those where the research interests of the individual authors are revealed, such as the chapters on 'Hypertelescopes', 'Intensity interferometry', and 'Nulling and coronography'. Here the presentation is excellent and the authors deploy rough order-of-magnitude calculations and physical arguments in amongst the text to very good effect. However, other chapters suffer from a lack of mathematical detail, and are perhaps less clear in elaborating how a rather small set of underlying physical principles govern the range of different experimental techniques that is covered. This is a pity, but perhaps points to the need for a treatment more akin to that in an advanced textbook for some of the topics.

Overall then, while not getting my 'five-star' rating — the coverage and quality between chapters is a little too variable, with some needing just a little more discussion to do justice to the subtleties of the arguments — this volume fills a gap that has for a long time been problematic. Some readers may be challenged by the parenthetic content that appears in the footnotes — the authors clearly enjoy broadening the minds of their readership — but that should not put off those who are seeking to test the water.

Interestingly, the final two chapters, which summarize astronomical results in the field and possible technology paths ahead, already look a little dated. This could be seen as a failing of the authors, but I prefer to interpret this as a positive reflection on how rapidly progress is being made in exploiting interferometry for astrophysics. And as an introduction to the field, this volume fills a valuable rôle. — CHRIS HANIFF.

Current Issues in Cosmology, edited by J.-C. Pecker & J. V. Narlikar (Cambridge University Press), 2006. Pp. 267, 25·5 × 18 cm. Price £60/$110 (hardbound; ISBN 0 521 85898 4).

This book, published in 2006, contains the proceedings of a colloquium held at the Collège de France in 2004 June. The rapid progress being made in modern astrophysics, particularly cosmology, should have convinced the organizers of this meeting and indeed the publishers that traditional proceedings such as these would be a waste of time and money. The long delays involved in printing such volumes means that they are irrelevant even before they are available. They are also ridiculously expensive, at a time when library budgets are under enormous pressure to save costs. All the best meetings nowadays simply put the speakers' talks on a web page, freely and instantly available for the entire research community.

Nevertheless, this book has been published so some people might be tempted to buy it. Even if they can afford the £60 needed, they should think carefully before investing. The mixture of articles is extremely eclectic, with some very interesting, others very dated, and the rest just plain silly.

In principle I like the idea of allowing sceptics the chance to question received dogma. It must have been fun to see the diehard Steady-Staters trying to fend off the compelling results that emerged from the *Wilkinson Microwave Anisotropy Probe* in 2003. But even in cosmology there is such a thing as the scientific method. For example, Wickramasinghe again expounds an explanation of the cosmic microwave background as starlight scattered off iron whiskers. If elongated grains do have exactly the correct dimensions then they can indeed thermalize starlight more effectively than traditional dust. But of course this model introduces free parameters that can be adjusted to fit the spectrum of the microwave background, whereas a thermal black-body needs only one: the temperature. Wickramasinghe's model seems desperately contrived to me. Ockham's razor can be applied to any whiskers, even if they are made of iron.

In among the oddities are some conventional review articles, but they go only part of the way towards redressing the balance. Part of the reason for this is that they are generally too short to be anything other than superficial. According to the jacket "this text will be valuable for graduate students and researchers in cosmology". Expensive, yes. Valuable, no. — PETER COLES.

Other Books Received

Highlights of Astronomy, Volume 13, edited by O. Engvold (Astronomical Society of the Pacific, San Francisco), 2005. Pp. 1085, 23·5 × 15·5 cm. Price $95 (about £53) (hardbound; ISBN 1 583 81189 3).

This enormous tome (7 cm thick) records the Joint Discussions and Special Scientific Sessions that took place at the 25th IAU General Assembly in Sydney in 2003 July. Of course, the material is now somewhat dated but nonetheless the volume presents a good record of the state of play in a wide range of astronomical activities at that time. One for serious astronomical libraries, although there seem to be fewer of them around these days!

THESIS ABSTRACTS

Photon-Dominated Regions: Development of a Time-Dependent Model and Application to Astrophysical Problems

By Thomas Bell

Photon-dominated regions (PDR) occur in many areas of astrophysical interest and an understanding of their underlying chemical and physical processes can provide an insight into the conditions within them. This thesis describes the development and implementation of a time-dependent version of the UCL_PDR model, including comprehensive benchmarking as part of an international effort to understand the differences between individual models and improve their agreement in key areas.

The code has been applied to calculate theoretical values of the CO-to-H_2 conversion factor, X_{CO}, to investigate its sensitivity to physical-parameter variation. X_{CO} is found to vary significantly from its canonical value under certain conditions, and by over an order of magnitude in the case of high density or low metallicity. By fitting observed line-intensity ratios in a sample of nearby galaxies, PDR models have been constructed to represent the conditions found in a range of galaxy types. These are used to derive appropriate values of X_{CO} for such objects and to investigate the possibility of using higher-transition lines of CO as more reliable mass tracers in those environments.

A parameter-space search has also been conducted using the model to look for conditions that produce significant column densities of H_2 with low levels of emission that would be undetectable or overlooked by current surveys. A plausible region of parameter space is found to produce such molecular dark matter, capable of concealing significant masses of gas that may form reservoirs for future star formation.

Additional applications of the UCL_PDR model are discussed, including a study of the chemistry within transient microstructure in the diffuse interstellar medium and models of the time-dependent expansion of a molecular shell around a massive star cluster, applied to observations of the central starburst in M 82. — *University College London; accepted 2006 November.*

Diffuse Interstellar Bands and the Structure of the ISM

By M. A. Cordiner

Results are presented of three different studies into the nature of the diffuse interstellar bands, their carriers, and the environments in which they are located.

(*i*) Optical observations of small-scale structure in the distribution of large molecules and/or dust grains in the ISM are examined in the first dedicated study of its type. Evidence is presented for variation in the strengths of 15 out of 16 measured narrow diffuse interstellar bands, over spatial scales from <370 AU to $<20\,000$ AU, observed towards the component members of nearby ($<1{\cdot}5$ kpc distant) early-type binary and multiple-star systems. Variations in diffuse-interstellar-band (DIB) equivalent widths of about 5–10% are found between the sightlines towards ρ Oph A and B (separated by approximately 370 AU in the plane of the sky). The λ5780, λ5797, λ5850, λ6376, λ6379, λ6439, λ6614, and λ6660 DIBs are found to be significantly stronger towards ρ Oph B by an amount comparable to the differences in the column densities of interstellar K I and Ca II in these sightlines. The upper limit on the variability of the λ6284 DIB is approximately 1·5%. Different DIBs are subject to different degrees of variation, and in some cases different signs of variation, for example, the λ5850 DIB is stronger towards ρ Oph C than ρ Oph A, whereas λ6614 is stronger towards A than C, proving the existence of chemical differences between the DIB carriers. The λ6614 DIB is found to show a variation in its pattern of sub-structure between ρ Oph A and C, which, interpreted within the 'Webster hypothesis' (A. Webster, *MNRAS*, **282**, 1372, 1996), is consistent with a $\sim 4\%$ enhancement in the interstellar $^{12}C/^{13}C$ ratio towards ρ Oph A relative to C. In other star systems observed: the λ5780, λ6196, and λ6614 diffuse interstellar bands are found to be stronger towards β^2 Sco than β^1 Sco (sightlines separated by ~ 2200 AU); the λ6614 DIB is found to be stronger towards HD 150136 than HD 150135 ($\sim 12\,500$ AU separation) but no significant variation is found in the strengths of any other DIBs in the spectra of this binary system; the λ5780, λ6196, and λ6614 DIBs are detected in the lightly-reddened sightlines towards the two members of the μ Cru system, and are found to be approximately 50 to 200% stronger towards μ^2 Cru than μ^1 Cru. Weak interstellar K I absorption is detected and is found to be $122 \pm 80\%$ stronger (at 1σ confidence) towards μ^2 Cru than μ^1 Cru.

The λ5780, λ6196, λ6203, and λ6614 diffuse interstellar bands are detected in the well-known 'time-variable' sightline towards κ Vel. Spectra are presented that show the interstellar K I column density in this sightline to be $N(\text{K I}) = 3{\cdot}43 \pm 0{\cdot}13 \times 10^{10}\,\text{cm}^{-2}$ in 2004 June, corresponding approximately to a 35% increase in N(K I) since the time of the last measurement in 2002 March by Crawford (*MNRAS*, **334**, L33, 2002). During this period, the sightline moved <5 AU. DIB strengths towards κ Vel are compared between observations made in 1995 January and 2004 June, during which time the sightline moved <25 AU across the interstellar medium (ISM) and the neutral-potassium column density approximately doubled. No significant variation in the strength of λ5780 is found, with an upper limit on the change in equivalent width of $\pm 41\%$.

The variation of diffuse interstellar band strengths over small spatial scales is interpreted as due to variations in the abundances of the carriers. Possible causes of small-scale DIB variability are discussed, including the degree of ionization and excitation of the carriers.

(*ii*) The hypothesis that the cyanomethyl anion CH_2CN^- is responsible for the relatively narrow diffuse interstellar band at 8037·8 ± 0·15 Å is examined. The absorption spectrum arising from the $^1B_1 \leftarrow ^1A'$ origin-band transition from the ground electronic state to the first dipole-bound state of the anion is calculated. Assuming that the distribution of ground-state rotational-level populations is in thermal equilibrium with the 2·74-K cosmic-microwave-background radiation, the transition results in a rotational contour with a peak wavelength of 8037·78 Å. CH_2CN^- is found to be a plausible candidate for the carrier of the λ8037 diffuse interstellar band provided a mechanism exists by which the rotational contour is broadened by an approximately Gaussian dispersion function with a width characterised by a Doppler *b* parameter between 16 and 33 km s^{-1}, depending on the specific sightline in which the DIB is observed. Doppler broadening is found to be sufficient to cause such a dispersion in heavily-reddened sightlines, as demonstrated by the velocity structure of the interstellar gas in the sightline towards HD 183143, which is examined for K I, Na I, Ca I, Ca II, Ti II, CH, CH^+, and CN. Convolution of the calculated CH_2CN^- transitions with the optical-depth profile of either Ca II or Ti II successfully reproduces the profile of the narrow λ8037 DIB observed towards HD 183143.

The 2·74-K thermal distribution of ground-state rotational-level populations may be modified by the nuclear-spin statistics of the molecule. This situation is modelled and results in the appearance of additional, strong, spectral features at around 8024·8 Å and 8049·6 Å that are not seen in the observed interstellar spectra. If (*a*) no chemical mechanisms exist for the conversion of 'ortho' CH_2CN^- (hydrogen nuclear spins parallel) to 'para' CH_2CN^- (hydrogen nuclear spins anti-parallel) or (*b*) the CH_2CN^- formation mechanisms do not result in a distribution of K_a'' levels approaching a 2·74-K Boltzmann distribution, then it is found that CH_2CN^- cannot be the carrier of the λ8037 diffuse interstellar band.

(*iii*) The strengths of diffuse interstellar bands and atomic lines in the ISM of the Large Magellanic Cloud (LMC) are analysed and compared with Galactic data. Using optical spectra obtained along six reddened sightlines towards early-type stars in the LMC, at a resolution of ~3 km s^{-1} and a signal-to-noise of ~200, the velocity structure and column densities of interstellar K I, Na I, Ca II, and Ti II are derived. Evidence is presented that the spectrum of diffuse interstellar bands in the LMC is similar (in strength and structure) to that found in the Galaxy, with the measurement of the equivalent widths of eleven DIBs at the Doppler-shifted wavelengths expected for the radial velocity of the LMC, including λ4430, λ5705, λ5780, λ5797, λ5850, λ6196, λ6203, λ6284, λ6376, λ6379, and λ6614. The observation of λ5705, λ5850, λ6196, and λ6203 constitutes the first reported detection of these DIBs in the LMC, and for λ5850, in any location outside of the Galaxy. All of the expected DIBs were observed towards the 30 Dor targets Sk –69° 223 and Sk –69° 243, and with strengths approximately equal to, or only slightly weaker than, those in Galactic 'σ-type' (strongly UV-irradiated) sightlines with similar reddenings and neutral-potassium column densities. This result shows that there are interstellar clouds in the vicinity of 30 Dor that provide favourable environments for the existence of DIB carriers. The velocities of the carriers of the λ5780, λ5797, λ5850, λ6196, λ6379, and λ6614 diffuse interstellar bands in the LMC are found to be coincident with the velocities of the peaks of the atomic column-density distributions at radial velocities of between 240 and 300 km s^{-1} relative to the local standard of rest. The least-squares-fitted velocity of the λ6614 DIB is found to be shifted by ~ +5 km s^{-1} relative to the other DIBs in three out of four sightlines. This may be interpreted as evidence that the profile of sub-structure of the λ6614 DIB is skewed towards the red in these three sightlines (Sk –68° 135, Sk –69° 223, and Sk –69° 243) to a greater degree than that found in the Galactic ISM.

Compared to Galactic trends, the LMC DIBs are found to be weak with respect to the reddening and neutral-potassium column density towards Sk –67° 2 and Sk –68° 135. This may be attributable to a combination of the high UV flux and reduced shielding of interstellar clouds due to the low metallicity of the interstellar gas of the LMC, and results in the destruction of DIB carriers by photodissociation and/or photoionization. Relative to *N*(H I) the λ6284 DIB observed in four LMC sightlines is shown to be approximately $^1/_5$ to $^1/_2$ of its average strength in the Milky Way. This supports the idea that the metallicity and/or dust-to-gas ratio of the ISM is closely linked with the chemistry that governs the abundance of DIB carriers relative to *N*(H I). Variations in the *N*(Ca II)/*N*(Ti II) ratio are found over at least an order of magnitude in the LMC ISM, and are taken as evidence for significant variation in the Ca II/Ca III ionization balance. Derived logarithmic titanium depletions are found to be relatively low in the six LMC sightlines studied, with values between approximately –0·8 and –1·9, which are similar to the levels of depletion generally seen in the warm, shocked interstellar medium of the Galaxy. — *The University of Nottingham; accepted 2005 August.*

Spectroscopic Analysis of the Winds and Atmospheres of Galactic B Supergiants

By Samantha Searle

Uncertainties in the post-main-sequence evolution of B supergiant stars exist because their evolution is controlled by variable mass loss from the star as well as rotation, binarity, and convection processes in the core. The latter effect leads to surface enrichment as the products of nuclear burning (carbon, nitrogen, and oxygen) are brought to the surface. However, current stellar-evolution models fail to predict the correct amount of CNO processing in massive stars. Accurate mass-loss rates are essential for underpinning the wind-momentum–luminosity relation and also for improving stellar-evolution calculations. Existing discrepancies between B-star mass-loss rates obtained from observations and those from theoretical predictions also emphasize the need for a better understanding of structured stellar winds. Recent improvements in stellar-atmosphere models to include full nLTE effects and line blanketing also provide us with the means to derive more accurate temperatures and luminosities, leading to a reduction in OB-star temperature scales.

An optical and ultraviolet quantitative spectroscopic analysis of the atmospheres and winds of galactic B supergiants is presented here. Fundamental parameters such as temperature, luminosity, mass-loss rate, and CNO abundances are derived for individual stars using the non-LTE, line-blanketed model-atmosphere code of Hillier & Miller. We present detailed temperature scales for B supergiants and discuss their implications. Additionally we discuss the derived mass-loss rates and CNO abundances for our sample of galactic B supergiants and compare them to other results.

Empirical analysis of the ionization conditions of early-B-supergiant winds has also been carried out (based on SEI modelling) and compared to model predictions from the stellar-atmosphere code of Hillier & Miller. This allows us to undertake a critical comparison of observed and predicted ionization behaviour in the wind, focussing on trends of the ionization fraction, q_i, with velocity, relative ionization strengths, and whether ions tend to increase or decrease further out in the wind. Values of $\dot{M}q_i$ (the product of the mass-loss rate and the ionization fraction) have been obtained from UV line-synthesis modelling and, using our derived mass-loss rates, values of q_i are acquired from $\dot{M}q_i$ for our sample of galactic B supergiants. Our studies show that values of q_i are much lower than expected and, furthermore, none of the ions (*e.g.*, Al III, Si IV, C IV, N V) are dominant in the wind, a surprising result since the highest values of q_i occur in the B spectral range. We discuss our most recent findings and their implications for clumping and structure in the wind. Most importantly these results provide strong evidence for a downward revision of mass-loss rates by *at least* an order of magnitude. This evidence demonstrates a clear need to review mass-loss-rate determinations and the rôle of clumping in massive-star winds. — *University of London, UCL; accepted 2006 September.*

The Formation of Satellite Galaxies and Their Associated Black Holes

By Noam Libeskind

The satellite galaxies of the Milky Way appear to be aligned in a great circle on the sky which is perpendicular to the Milky Way's disc. This anisotropic distribution of satellite galaxies has been reproduced using semi-analytical modelling in conjunction with high-resolution *N*-body simulations. Using hydrodynamic simulations we also look at the sense of the anisotropy with respect to the central galaxy. We look at the alignment between the angular momentum of a galaxy, its satellite distribution, and the dark halo. The satellite-galaxy luminosity function is reproduced including the number statistics at the bright end. Additionally, if black holes inhabit all stellar spheroids then in an hierarchical universe one would expect black-hole coalescence to be a frequent occurrence. Such merging will result in a gravitational recoil. We study the effect such recoil has on the $M_{\rm BH}$–$M_{\rm Bulge}$ relation and are able to constrain the still-not-fully-understood physics of gravitational recoil to values in agreement with gravity calculations. Also, we quantify the expected properties of the resulting extragalactic black-hole population. — *University of Durham; accepted 2006 September.*

A High-Accuracy Synthetic H_2O List: Computation and Application

By Robert John Barber

The subject matter of this PhD thesis is the production and application of the Barber–Tennyson line list, *BT2*, a computed list of $H_2{}^{16}O$ transition frequencies and intensities. *BT2* was produced at UCL using a discrete-variable-representation two-step approach for solving the rotation-vibration nuclear motions (Tennyson *et al.*, *Comp. Phys. Comm.*, **163**, 85, 2004). It is the most complete water line list in existence, comprising over 500 million transitions ($\sim$65% more than any other list) and it is also the most accurate (over 90% of all known experimental energy levels are within $0 \cdot 3$ cm^{-1} of the *BT2* values). Its accuracy has been confirmed by extensive testing against astronomical and laboratory data.

The line list has already found widespread application in a wide range of astrophysical environments. It has been used to identify individual water lines in the spectra of comets, sunspots, cool stars, brown dwarfs, and the enigmatic object V838 Mon; and in a number of cases physical parameters have been derived from the intensities of the lines. The line list has also been used to model the atmospheres of cool stars and brown dwarfs and the chemistry of the circumstellar molecular shell ejected by V838 Mon.

In addition to our own work with *BT2*, we have supplied various data, derived from *BT2*, to other astrophysical research groups including N. Dello Russo and co-workers for cometary applications; J. M. C. Rawlings for modelling the time-dependent chemistry of the shell ejected by V838 Mon; and P. Hauschildt's stellar atmospheric modelling group, which has included the complete *BT2* line list in its PHOENIX database.

Practical applications of *BT2* are not confined to the field of astronomy. The line list is now the preferred reference tool for many groups engaged in the identification of water lines in high-temperature laboratory torch spectra, and we have been pleased to supply them with appropriate *BT2* spectral data.

This thesis describes both the production and application of our line list. The final chapter looks to the future, which includes further applications of *BT2* and the production of an NH_3 line list. — *University of London, UCL; accepted 2006 November*.

The thesis is available electronically at:
http://www.homepages.ucl.ac.uk/~ucaprjb/thesis_final.pdf.

OBITUARY

Raymond James Cohen (1948–2006)

R. J. Cohen, one of Britain's leading radio astronomers, who died suddenly on 2006 November 1, devoted his research to the understanding of the physics behind the formation and evolution of stars but also carried out a key international rôle in the protection of the frequency bands used by radio astronomers to observe the Universe.

Jim, as we all knew him, was born in 1948 in Brisbane, Australia, the eldest of five children. The family, though relatively poor, had a house filled with books and the children were expected to get 'A's in all their school work. His father, an industrial designer, whistled classical music as he pursued his hobby of cabinet making and gave Jim his lifelong love of music as, over the years, he became an expert player of the recorder, whistle, and flute, which he played in his own ceilidh bands, Merlin and Hartigan's Fancy, and the local amateur orchestra.

During the holidays while attending high school, he visited his uncle in Sydney where his interest in astronomy was awakened by viewing the stars, Moon, and planets through the six-inch reflector his uncle had built in his back yard. In 1970, after gaining his bachelor's and master's degrees in science and mathematics at the University of Queensland, he was awarded a Commonwealth scholarship to the University of Manchester's Jodrell Bank Observatory, where he studied for a PhD in radio astronomy.

His academic ability was quickly recognized and he remained at Jodrell Bank, first as a research fellow and then as a lecturer. He was promoted to Reader in 1994. He always enjoyed teaching and, before his untimely death, was preparing a new course on stellar astrophysics, writing a textbook on radio astronomy, and updating parts of the *Oxford Dictionary of Astronomy*. During his career he supervised 27 postgraduate students, several of whom are now making their own mark in astronomy.

Jim's major astronomical contributions, published in more than 150 scientific papers, made much use of the high-resolution capabilities of Jodrell Bank's 217-km *MERLIN* array to study astronomical masers that are linked with star formation. Those radio beacons allowed him to understand how magnetic fields influence the birth and ageing processes of stars and gained him an international scientific reputation.

In recent years he led a consortium of nearly 20 astronomers, from Britain and his native Australia, surveying the Milky Way for methanol masers that pinpoint the sites of the youngest stars. In 2002 the consortium won funding for a new 'multi-beam' receiver that would allow the survey to be completed within a few years rather than several decades. Completed in 2006 January, it is now in use on the *Parkes Telescope* in Australia, where the view of the central regions of our Galaxy is better than from the United Kingdom; Jim was present as the instrument achieved first light. Nearly half of the important regions accessible in the Southern Hemisphere have now been observed and the results are fulfilling all expectations. It is tragic that he will not be able to further this work himself. Later this instrument will come to Jodrell Bank to carry out his plan to search for neutron stars from the Northern Hemisphere — a survey which will be a lasting memorial to Jim's scientific career.

No less important was Jim's work on the protection of the radio environment. From 1995 to 2000 he was chairman of the European Science Foundation's Committee on Radio Astronomy Frequencies (CRAF) and, with his quiet but highly effective negotiating skills, played a major rôle in protecting the radio astronomy bands from the *Iridium* and *GLONASS* satellites. In 2003 he became President of IAU Commission 50, on the Protection of Existing and Potential Observing Sites, which was responsible for both radio and optical spectrum management. The astronomical community will be forever in his debt for his dedicated and tireless work on their behalf.

Jim was a quiet, friendly, and gentle man, a great friend and colleague. He will be greatly missed by all who knew him. — IAN MORISON.

Here and There

ARE THEY ACCRETING?

The First High Resolution Spectra of 1·3 L Subdwarfs — *AJ*, **131**, 1806, 2006.

UNLUCKY FOR SOME

… the Zodiac has been joined by a 13th constellation, Ophiuchus, which makes astrological horoscopes hopelessly wrong. — *The Daily Telegraph*, 2006 June 5, June Night Sky

ADVICE TO CONTRIBUTORS

The Observatory magazine is an independent journal, owned and managed by its Editors (although the views expressed in published contributions are not necessarily shared by them). The Editors are therefore free to accept, at their discretion, original material of general interest to astronomers which might be difficult to accommodate within the more restricted remit of most other journals. Published contributions usually take one of the following forms: summaries of meetings; papers and short contributions (often printed as *Notes from Observatories*); correspondence; reviews; or thesis abstracts.

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(1) G. H. Darwin, *The Observatory*, **1**, 13, 1877.
(2) D. Mihalas, *Stellar Atmospheres (2nd Edn.)* (Freeman, San Francisco), 1978.
(3) R. Kudritzki *et al.*, in C. Leitherer *et al.* (eds.), *Massive Stars in Starbursts* (Cambridge University Press), 1991, p. 59.

Journals are identified with the system of terse abbreviations used (with minor modifications) in this *Magazine* for many years, and adopted in the other major journals by 1993 (see recent issues or, *e.g.*, *MNRAS*, **206**, 1, 1993; *ApJ*, **402**, i, 1993; *A&A*, **267**, A5, 1993; *A&A Abstracts*, §**001**).

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