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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2010 January 8 at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

A. C. FABIAN, *President*
in the Chair

The President. My first announcement is of course to wish everyone a happy New Year. Also, on behalf of the Society I would like to congratulate Dr. David Kerridge FRAS, of the British Geological Survey in Edinburgh, for the award of an MBE in the New Year Honours list.

At our meeting of December 11 we agreed to make the following awards for 2010: the Gold Medal for astronomy is awarded to Professor Douglas Gough of the Institute of Astronomy in Cambridge; the Gold Medal for geophysics, to Professor John Woodhouse of the University of Oxford; the Herschel Medal, to Professor Jim Hough of the University of Hertfordshire; the Jackson-Gwilt Medal to Professor Craig Mackay of the Institute of Astronomy in Cambridge; the Chapman Medal, to Professor Bernard Roberts of the University of St. Andrews; the Fowler Award for Astronomy, to Dr. Barbara Ercolano of the Institute of Astronomy in Cambridge; the Fowler Award for Geophysics, to Dr. Ineke de Moortel of the University of St. Andrews; the Winton Capital award for astronomy, to Dr. Elizabeth Stanway of the University of Bristol; the Winton Capital award for geophysics, to Dr. David Robinson of the University of Oxford; the Award for Service to Astronomy, to Professor Francisco Sánchez of the IAC; the Award for Service to Geophysics, to Dr. Frank Lowes of the University of Newcastle-upon-Tyne; the Group Achievement Award for Astronomy is awarded to the *SuperWASP* team; the Group Achievement Award for Geophysics is awarded to the CHIANTI consortium; the 2010 George Darwin Lectureship is awarded to Professor Carlos Frenk at the University of Durham; and the 2010 Harold Jeffreys Lectureship, to Professor Steve Miller of University College London. And the following have been made Honorary Fellows: Professor Doug Lin of Santa Cruz and Director of the Kavli Institute of Astronomy in Beijing, Professor Richard Larson of Yale University, Professor Conny Aerts of the University of Leuven in Belgium, Dr. Wlodek Kofman from Grenoble, and Professor Domenico Giardini of the ETH in Zurich, Switzerland.

Let's press on with our programme, and our first speaker is Allan Chapman of Oxford talking on 'The 80th anniversary of the RAS discussion meeting on Expanding the Universe'.

Dr. A. Chapman. Eighty years ago, the international astronomical community was in something of a quandary. For over the preceding three decades, new breakthroughs in observational data and in theoretical interpretation in physics and cosmology had begun to challenge what might be called the 'post-Newtonian' and 'post-Herschellian' universe — a universe that dated back to the 18th Century, in which space and time were absolutes, where a steady state prevailed, as burned-out stars provided the stuff out of which the nebulae and new stars were made, and in which everything had been contained within one vast stellar system, with the Sun apparently at the centre. This big Milky Way had been challenged by certain 19th-Century cosmologists who speculated that the dim nebulae might well be remote 'island universes', and Milky Ways in their own right. After all, the large reflecting telescopes of Lord Rosse and William Lassell had revealed spiral structures in a dozen or so of the 6000 recorded nebulae. So did the Laws of Universal Gravitation act within them?

But the development of stellar spectroscopy and increasingly refined photographic techniques in the late 19th Century suddenly acquired a new cosmological potential by the first decades of the 20th Century, when combined with the optical and mechanical engineering of a new breed of large American telescopes set up in 'prime sky' mountain and desert locations. And of particular significance in this respect were the Mt. Wilson, Flagstaff, and Lick Observatories.

One of the earliest fruits of this work was Henrietta Leavitt's discovery in 1912 of a period–luminosity relationship exhibited by Cepheid stars in the Magellanic Clouds. This was to provide a crucial technique whereby in the years ahead these 'standard candles' could be used to calibrate the distances of 'nebulae', or galaxies.

But of central importance to the early-20th-Century cosmological debate was Vesto Slipher's discovery, made at the Lowell Observatory, Flagstaff, Arizona, between 1912 and 1917, that a spectroscopic Doppler shift was exhibited by certain nebulae. Indeed, of 25 nebulae which he had studied by 1917, he found that 21 were receding from us.

By the 1910s, cosmological data began to increase rapidly, and in many respects, in hindsight, 1917 became something of a pivotal year for both the observational and the theoretical astronomers. For in that year not only did Slipher publish his paper on the red- (and blue-) shifted nebulae, but also the great 100-inch *Hooker* reflector on Mt. Wilson came into use, which was by far the most powerful telescope in the world. And in 1917 too, Willem de Sitter, of Groningen in Holland, published his own mathematical model for the Universe, which shared many theoretical features with Einstein's recently-announced relativistic universe. Both the Einsteinian and de Sitter universes incorporated the cosmological constant, were curved, and were also static. But where de Sitter's universe was remarkable was in the respect that it contained no matter whatsoever, but was empty, giving rise to the observation that while Einstein's universe contained matter but no motion, de Sitter's involved motion (theoretical) without matter.

The third decade of the century began with the so-called 'Great Debate' between Harlow Shapley and Heber Curtis on 1920 April 26. In this ingenious yet inconclusive discussion, Shapley presented a case, based on globular-cluster measurements, for a very big single-galaxy universe, 300 000 light-years across and with the Sun some distance from the centre. Curtis of Lick, however, argued for island universes, and with M31 around 500 000 light-years away. Both men made valuable points, yet what was lacking was conclusive evidence one way or the other. This uncertainty was in no way helped by the fact that at this time no one was quite sure why light was red-shifted in the first place: was it caused by a genuine Doppler-effect recession of the object — which sat incongruously with Einstein's and de Sitter's static, non-dynamic universes — or was it something that somehow happened to light traversing vast distances of space?

This deadlock was broken on 1925 January 1, when Edwin Hubble of the Mt. Wilson Observatory published an epochal paper. For Hubble announced, from his observation of more than a dozen Cepheid variable stars in the M31 and M33 'nebulae', and using the Leavitt and subsequently Shapley period–luminosity law, that these objects must be hundreds of thousands of light-years away, thereby invalidating Shapley's 'Big Galaxy' cosmos. Then in 1929 Hubble published the paper that would have such a profound effect on the future of cosmology. On the basis of his own, Milton Humason's, and Vesto Slipher's galaxy-red-shift work, Hubble propounded his velocity–distance relationship law: namely, that the recessional velocity of the galaxies increased with their distance. And though the actual figures involved have got larger in the wake of a greatly expanded database over the past 80 years, the essential mathematics of 'Hubble's Constant' or law still holds. And while Hubble was not a theoretician, or engaged in theoretical interpretation, his Constant contained the observational seeds of what would come to be seen as the 'Expanding Universe'.

Then, at the 1930 January 10 Royal Astronomical Society meeting, Willem de Sitter presented a paper on the relationship between the velocities of spiral nebulae and their scale and angular-size computed distances. Plotted graphically, they came close to a straight line, very similar to Hubble's velocity–distance graph of the year before. Of course this was explicable in accordance with de Sitter's theoretical empty universe which was axiomatically static (yet in which Doppler-shift recession became possible when matter was introduced), but not with Einstein's real, material, curved, static universe which could not, at that point, accommodate expansion.

De Sitter's paper was duly published in *The Observatory*, but on its arrival at the Catholic University of Louvain, Belgium, it immediately produced a response, in the form of a letter to Professor Arthur Eddington from Father Georges Lemaître. Lemaître pointed out that in 1927 he had published a paper in Brussels suggesting the possibility of an expanding universe (as also had Alexander Friedmann back in 1922). Eddington, who, like de Sitter, was deeply impressed by Lemaître's expanding model, had a translation made of his 1927 Brussels paper, which was published in *Monthly Notices of the Royal Astronomical Society* in 1931. Rather frustratingly, the surviving draft of Lemaître's letter to Eddington is undated, but it must have been written in 1930 February or March. What is certain is that both Eddington and de Sitter were rapidly converted to Lemaître's expanding model, and by 1930 May were actively arguing in its favour.

Lemaître became fascinated by the idea that, if everything was receding, one might be able to trace things back to a 'primal atom'. Of course this was a long, long way from what would become the 'Big Bang' theory, though Lemaître's mathematical and interpretational work had undoubtedly laid the foundations. For Lemaître's universe, unlike de Sitter's, contained matter, but unlike Einstein's, it was not static, and shared several features with Friedmann's cosmology.

It would take much more observational and theoretical work, however, including that of George Gamow, to produce a truly convincing Big Bang cosmology. But what cannot be denied is that, when seen in historical context, it was de Sitter's paper given at the 1930 January 10 Royal Astronomical Society meeting and the ensuing discussion that tipped the balance in favour of what would later come to be seen as a Big Bang cosmology.

For more about the beginnings of modern cosmology, see Harry Nussbaumer's and Lydia Bieri's fascinating newly-published book, *Discovering the Expanding Universe* (CUP, 2009).

Professor D. Lynden-Bell. I would like first to agree with you, that it's very much the advance of technology which leads to progress, and to bring that out particularly, Slipher measured his 25 redshifts of galaxies from the 36-inch at Flagstaff and he said that this field would not go very much further because each of these spectra took four or five nights of observation — that was the difficulty of taking nebular spectra.

Dr. Chapman. I'm very glad you brought that up because work was also going on at Lick as well as at Flagstaff. Yes, even the best plates of 1912–13, when Slipher was doing this fundamental work, were so slow that you had to depend on impeccable engineering of the drive mechanisms: you can have maybe eight or ten hours of observation, then shut the plate down, come back the next night, and hope the spectral lines will fall in the same place. And of course, the problem was discovered by Huggins, when he had great difficulty in obtaining his spectra with wet plates in the early 1870s. That is a very important point and I'm glad you brought it up. The sheer tedium, and the sitting at the eyepiece by the observer, of keeping that field bang on the centre of a disc, probably by a guide star, must have made watching paint dry seem good. [Laughter.]

Professor Lynden-Bell. Just one other point: Slipher did actually manage to measure the rotation of M 104, the Sombrero, and find that very large velocity that we now know; so that must have already made people think that the galaxies were far away.

Dr. Chapman. Yes, even Lord Rosse, 60 years earlier, was asking, from its shape, whether M 51 might be rotating – hence its appellation 'The Whirlpool'. I think that his great telescope showed some kind of structure in about 13 nebulae, which accorded with his belief that they were what Sir William Herschel spoke of as 'congeries' of stars. And of course, they were very much concerned with trying to detect a rotation over time, which might lead to being able to measure nebula distances.

The President. Well, I hope that the RAS continues to host talks of such importance. Thank you. [Applause.]

The next talk is by Bob Argyle from Cambridge, on the *PISCO* project.

Mr. R. W. Argyle. I want to talk about the *PISCO* project which is being carried out in collaboration with Drs. M. Scardia and L. Pansecchi at the Osservatorio Astronomico di Brera-Merate, Italy and Dr. J.-L. Prieur at the Laboratoire d'Astrophysique de Toulouse-Tarbes, Université de Toulouse, France.

PISCO stands for *Pupil Interferometry Speckle Camera and Coronagraph*. It is a multi-functional instrument which can be used (among other things) to carry out speckle imaging of visual binary stars. The instrument was built between 1991 and 1993 at the Observatoire de Midi-Pyrénées by Dr. Prieur and colleagues and was first used at the 2-metre *Telescope Bernard Lyot* at the Observatoire de Pic du Midi. In 1999 the time-allocation panels of that observatory were no longer allocating telescope time, so at the end of 2003 the instrument was transferred to Merate, some 30 km north-east of Milan where it was fitted to the 1·02-metre Zeiss reflector and has been in regular use ever since, producing to date more than 2000 high-quality measurements.

PISCO is capable of a number of tasks. It can function in spectroscopic mode by means of grisms, as a coronagraph, and carry out aperture synthesis *via* pupil masks, as well as the full-pupil mode using a range of eyepieces and filters in order to take short-exposure, high-magnification frames of visual binary stars. In the latter case too, a pair of controlled Risley prisms automatically correct for atmospheric dispersion depending on the altitude of the astronomical object to be observed. It is on visual-binary-star measurement that the rest of this talk will concentrate.

Large telescopes produce images of stars which are spread out into a time-averaged structure called the seeing disc under the influence of atmospheric turbulence. The seeing disc may be typically 1 arc second in diameter but very short exposures, typically 10 milliseconds, taken at high magnification, reveal structures called speckles which represent diffraction-limited information. If a star is a close double then pairs of speckles separated by the angular separation, ρ, of the double star can be seen in each short exposure. The speckles could be measured from these frames to yield separation and position angle (θ), but a more elegant and effective way to obtain the data is to use Fourier techniques. The Fourier transform assesses the essence of the frequency of spatial speckle separation, and the power spectrum shows a set of fringes. By transforming again this image, the autocorrelation is formed and this appears as a central spot with the equidistant satellite images in which the orientation and spacing of the satellite images are directly related to position angle and separation.

In order to produce suitably magnified images, *PISCO* has two eyepieces available which produce effective image scales of 0″·032 per pixel with a 10-mm eyepiece and 0″·075 per pixel with a 20-mm one. The images are captured using an intensified CCD camera which belongs to the University of Nice. To measure the autocorrelation images, circular apertures are chosen to enclose comfortably each satellite image with part of the surrounding field to estimate the background, and each image is measured with a linear and logarithmic look-up table applied. The centroid of each image is determined using two different reduction methods: barycentric calculation, and fitting the centre of the image with a Gaussian. We repeat the procedure at least four times for each object, which leads to a series of at least eight separate measurements for both ρ and θ. The angular scale of the images on the detector is determined using a full-size objective grating over the aperture of the telescope. Its orientation is calibrated with star tracks obtained when stopping the telescope motors. As a result, the formal error on *PISCO* measures is 0°·6 and 0″·01 in θ and ρ, respectively.

To determine masses of double stars, it is first necessary to fix the apparent orbit, which is done by measuring the relative position (ρ and θ) of the fainter component of the double star with respect to the brighter one with time. This can be done with much greater accuracy with the speckle technique than was possible with visual measurement, but orbital analysis is still reliant on historical measures due to the length of orbital periods involved — typically a few years to hundreds or thousands of years.

Once the apparent orbit is defined, the true orbit can be determined by one of the methods described in the astronomical literature, and from the size of the semi-major axis, a, and period of revolution, P, the total stellar mass in the binary in terms of the Sun's mass can be computed using Kepler's Third Law if the parallax, π, is known. Because the masses (and therefore the observational errors in these masses) depend on higher powers of a, π, and P, it is necessary to determine these latter quantities as accurately as possible.

As an example, the bright binary star γ Virginis illustrates the benefit of having a dedicated telescope capable of accurate measurement. The pair, which has a period of 169 years, passed through periastron in the spring of 2005 when the angular motion was one degree in five days. Regular and precise measures by *PISCO* over several years showed that the motion was Keplerian, thus disproving the suggestion that there might be a third body in the system. The resulting orbital period was refined to an accuracy of four days, and using the revised *Hipparcos* parallax the mass of the two F0 dwarf stars is 2·74 $M_{\odot}$, with a formal error of 2·2%.

Since its installation at Merate, the work done with *PISCO* has resulted in 13 papers in refereed journals and meetings proceedings, and the determination of 27 new or revised orbits. The *PISCO* team is now looking to improve both the efficiency of the detector and to increase the telescope aperture available. Negotiations are underway with the Observatoire de la Côte d'Azur to use *PISCO* on the 1·5-metre 'Laser-Lune' telescope at the Plateau de Calern in south-eastern France. Funding is being sought to purchase an Electron Multiplying CCD and the combination of these two factors will increase the magnitude limit achievable by *PISCO* by about 3 magnitudes, allowing the measurement of closer and fainter binaries, in particular those at the lower end of the main sequence. [Applause.]

The President. Thank you, Bob. I remember the drink, isn't it called a pisco sour? I must have had one at some point. Where is Calern?

Mr. Argyle. It's near Caussols, inland from Nice. It's the Plateau de Calern, so it's slightly higher up.

Dr. G. Q. G. Stanley. You said the original data was being transferred to video disks, or tapes I think. Are they still archived there or have you moved over to hard drives?

Mr. Argyle. No, we've decommissioned the video recorder and the data are now written straight onto hard drive. All the mean data frames, including the early ones, have been saved; they are on hard disk.

The President. Well good luck with that, Bob. We now move to Alan Fitzsimmons from Belfast, who's going to tell us about 'The impact of 2008 TC3'.

Professor A. Fitzsimmons. [The speaker described the discovery of the near-Earth object (NEO) 2008 TC3, and its impact with the Earth 19 hours after it was first detected; it is currently the only known celestial body for which certain impact with the Earth has been able to be predicted.

The speaker briefly reviewed the status of the various ongoing NEO surveys, such as LINEAR, the Catalina Sky Survey, and the Spacewatch survey. These programmes, using wide-field telescopes up to 1–2-m aperture, repeatedly image the sky to search for objects on Earth-crossing orbits. Since the mid-1990s, this effort has discovered the majority of the population of ~ 1-km-sized NEOs that it was designed to detect, now numbering about 1000; detections of smaller objects down to about magnitude 20 or 21 are being provided by the Catalina Sky Survey, which is also operating in the southern hemisphere. The discovery rate of NEOs in 2010 stands at about 700 per year. The results of these surveys can be translated into a size distribution for NEOs (approximating a power law), and hence probabilities of Earth impact. At the date of the meeting, the known NEOs within 1·3 AU of the Sun numbered 6734, with the number of those known to be on a collision course with the Earth being exactly *one*: and that had already hit us! [Laughter.]

Describing the timeline from discovery to impact, the speaker reported that the discovery image of 2008 TC3 was made on 2008 October 6 by the Catalina

Sky Survey 60-inch telescope on Mount Lemmon, with the object being observed for a couple of hours up to about 0900 UT. It was relatively bright at about $V \sim 19$, and its rapid motion at a rate of 5 arcseconds per minute indicated it was probably in near-Earth space. A good orbit calculation was possible following recovery of the object by Australian telescopes later that day, and the Minor Planet Center (MPC) and JPL orbit codes indicated that the object would pass within one Earth radius in the early hours of the morning of October 7, impacting over northern Sudan, less than 20 hours after discovery. A nominal albedo indicated an object about 3-m across, and not expected to survive the impact.

The MPC electronic circulars triggered many follow-up observations from observatories around the world, until the object was lost as it moved into the Earth's shadow at about 0145 UT on October 7. For example, a two-hour photometric light-curve from images acquired at the Clay Center Observatory showed rapid variation due to the object's 50-second rotation and 97-second precessional periods; the data quality was good enough to permit an accurate shape model of the asteroid to be produced.

The speaker described how with some serendipity — or prescience — he had submitted seven months earlier an observing proposal to use the *WHT* for a programme entitled 'Compositions of NEOs and the next impactor', to perform broad-band, visible–NIR spectroscopy of small NEOs. In this spectral region are found wide, solid-state absorption bands which are diagnostic of certain asteroid types, for example, silicate absorption features in the near IR; other spectral features are more characteristic of the so-called C-class asteroids, which appear to be more primitive and contain more volatile species, similar to carbonaceous-chondrite meteoritic samples. It so happened that two nights had been scheduled for this programme, on October 7–8; hence, an observing team on La Palma was ready and available, and arranged a time swap with the *WHT* observers on the night of October 6–7 to obtain spectra of the brightening $V \sim 16$ target, now racing at about 36 arcseconds per minute. The spectral results show a relatively featureless spectrum with a small dip indicative of weak silicate absorption, characteristic of a relatively rare B/F-class ('flat' spectrum) asteroid.

The impact of 2008 TC3 in the Earth's atmosphere occurred at 02:45:40 UT and was detected in *Meteosat* images, and by an infrasound array in northern Kenya which detected the atmospheric pressure wave. However, there have been very few ground-based reports of the event: one eyewitness report comes from the pilot and co-pilot of a KLM flight from Johannesburg to Amsterdam, about 1500 km from the impact, who saw flashes over the horizon.

From the various evidences, it has been concluded that the asteroid impacted at a shallow angle at about 12 km s^{-1}, with an impact energy of about 6×10^{12} J. Meteorite samples have been successfully recovered in expeditions led by Peter Jenniskens (NASA) and Muawia Shaddad (University of Khartoum), as reported in *Nature* (**458**, 485, 2009). From these samples, it has become clear that the object is very rare, a dark, carbon-rich mixture of silicates which have been thermally processed, known as a polymict ureilite. The material is highly porous, having a bulk density of about 2–3 g cm^{-3}. The low albedo indicates that the asteroid dimensions were about $6 \times 4 \times 2$ metres, with a mass of about 80 tonnes.

The publication of the lab spectrum of the meteorite showed a perfect match with the *WHT* spectra: this work demonstrates the first definitive link between an F-class asteroid and a recovered meteorite, albeit a rare type, and revealing that F-class asteroids are indeed the parents of ureilite meteorites. In summary, the key successes in this story are the rapid and accurate prediction of the impact following discovery, the characterization of the asteroid spectrum in pre-impact observations, and the fragment recovery providing the first direct link between an asteroid class and the mineralogy and chemistry of meteorites.]

Rev. G. Barber. Are F-class asteroids more predominant amongst the NEOs?

Professor Fitzsimmons. Not that we can see. Looking at the spectroscopy of the larger NEOs, F-types are extremely rare. One of the reasons we've been doing this survey of small NEOs is to see if the mineralogy of the small objects matches the large objects, but these seem to be pretty rare, so this was a real fluke.

Dr. P. Wheat. There are lots of radars looking at space debris and spacecraft. Was this object picked up on radar?

Professor Fitzsimmons. I can only say 'no' because I'm sure somebody would have been shouting out about it if they did. However, with radar you need to know what you are looking for before you detect it, in some sense: you need to know, for example, what the object's relative radial velocity is so you can tune the expected frequency of the return pulse actually to detect it. So, for example, the radars looking at satellites in low-Earth orbits would probably not have seen this because it would have had a much higher velocity relative to Earth, but of course they would also have to be looking at the right place at the right time. I certainly haven't heard anything about any radar detections.

Dr. Chapman. Are there any known mortalities from being hit by one of these objects?

Professor Fitzsimmons. There are no confirmed mortalities of any impact in modern times. Now, in historical records there are some intriguing reports of a rain of stones in China in which people were killed — I believe this was perhaps a couple of thousand years ago — which could have been something like this, but it's difficult to know. It's not my field, I must admit, but certainly in modern times there has been no report of any mortality, although there was a report that in Egypt a dog was killed by a meteorite in 1910.

The President. There's a nice picture on the web of a car that's been hit.

Dr. S. Eves. You showed one set of data, but was there more than one spectral band collected?

Professor Fitzsimmons. The spectrograph we use on the *WHT* actually has two arms: a red arm and a blue arm. The data I showed were from the red arm; there were also data collected simultaneously on the blue arm at shorter wavelength but unfortunately I don't believe the spectrum is reliable. The reason for that is in the hurry to get everything done we had a relatively narrow spectroscopic slit: in the red we know that we didn't suffer too much from differential dispersion, but as you go into the blue we suffered more slit losses; so that spectrum wasn't as accurate and we discarded it.

The President. Thanks very much, Alan. That was very interesting. And now our last talk is from Matt Griffin, and he'll talk about 'The first scientific results from *Herschel*'.

Professor M. Griffin. ESA's *Herschel Space Observatory* was launched in 2009 May, and, after several months of commissioning and performance verification, has now carried out many science-demonstration observations. Some results were shown at the *Herschel* Initial Results meeting in Madrid on December 18 and 19. It is a great pleasure for me to present to the RAS some highlights from that meeting, to illustrate the success and scientific power and promise of *Herschel*. A very large number of people have contributed to this endeavour over the years — people too numerous to mention from the instrument teams, from ESA, from European industry, and from the scientific consortia who have proposed the observations and worked on the data.

To begin with, I will summarize the essential features and the scientific rationale of the mission. *Herschel* is the first large-aperture FIR/sub-mm space mission, and the first to extend beyond 200 microns wavelength. It carries a 3·5-m-diameter telescope (the largest astronomical telescope yet flown), passively cooled to around 80 K, and three cryogenically cooled scientific instruments. *PACS* has a far-infrared camera operating at 70, 100, and 160 microns, and an imaging grating spectrometer covering 55–210 microns. *SPIRE* has a three-band submillimetre camera operating simultaneously at 250, 350, and 500 microns, and an imaging Fourier-transform spectrometer (FTS) covering 194–670 microns. *HIFI* is a seven-channel, single-pixel, high-resolution heterodyne spectrometer covering most of the submillimetre region. This suite of instruments allows astronomers to carry out sensitive imaging and spectroscopy over a decade in wavelength (about 60–670 microns). *Herschel* has been placed in an orbit around the Sun–Earth L2 point (a position 1·5 million km distant from Earth, on the anti-sunward side). It will have an operational lifetime of at least three years.

Herschel's main scientific objectives are: to carry out extragalactic and Galactic surveys to measure star-formation activity throughout cosmic time and in our own and nearby galaxies today; to make detailed studies of the physics and chemistry of the interstellar medium and the stellar/interstellar life-cycle in the Milky Way; and to perform spectroscopic and photometric studies of comets, asteroids, and the outer-planet atmospheres and their satellites. Most of *Herschel*'s observing time is open to the international community. About 18 months' worth of time has already been allocated to 42 Key Projects, and the next call for proposals will be issued in the spring of 2010.

The in-flight performance of the observatory is excellent. The telescope is in perfect alignment and focus, and the level of stray light is extremely low. The photometric and spectroscopic performance of *PACS* is generally comparable to pre-flight predictions, and that of *SPIRE* is slightly better than predicted for the camera and considerably better for the spectrometer. *HIFI* also performs well, but has been switched off since August due to an on-board electronics problem that has now been resolved. *HIFI* will be switched on again in early January for completion of its commissioning and performance verification.

The science-demonstration observations have been taken from the Key Projects already awarded. I will present just a few examples of the results presented at the Madrid meeting in December (the meeting presentations are all available on the ESA *Herschel* Science Centre website at http://herschel.esac.esa.int/).

More than 1500 hours of *Herschel* time will be devoted to deep extragalactic blank-field surveys with *PACS* and *SPIRE* in the form of three Key Projects (Hermes, PEP, and ATLAS), addressing important scientific issues such as the resolution of the cosmic infrared background, number-count models, bolometric (as opposed to single-band) luminosity functions, formation and evolution of galaxy bulges and ellipticals, structure formation, the relationship between star formation and environment, cluster properties and evolution, the history of energy production, the AGN–starburst connection, cosmic-infrared-background fluctuations, and much more. *SPIRE* science-demonstration maps of 4×4-degree areas have superb data quality with many thousands of galaxies detected, and show that *SPIRE* can integrate down to its own confusion limit very rapidly. Observations of smaller fields with *PACS*, which has a smaller beam size and so a lower confusion limit, are able to resolve a significant fraction of the sources responsible for the background. Both instruments have made deep and high-quality observations of a massive cluster, Abell 2218, which are allowing the magnification of background galaxies by gravitational lensing to achieve a sensitivity better than the blank-field confusion limit. *SPIRE* maps illustrate the progress made in submillimetre astronomy in the ten years since the initial *SCUBA* 850-micron observations of the Hubble Deep Field in 1998. In that observation, five sources were discovered after 20 nights of observation; in a typical 16-hr observation of a 4×4-degree field, *SPIRE* detects around 15 000 galaxies.

Detailed study of nearby galaxies is one of the most interesting areas of *Herschel* research, and eight major Key Programmes are already underway in this area, all of which presented their initial results in the Madrid meeting. This included systematic investigations with *SPIRE* of dust in galaxies in the Virgo cluster, high-angular-resolution imaging of the interacting galaxies NGC 4038/9 (the Antennae) with *PACS*, and large-scale *SPIRE–PACS* parallel-mode imaging of part of the LMC. The *PACS* spectrometer has been used to make spatially resolved spectroscopic observations of fine-structure lines in M 82 and other nearby galaxies, and the *SPIRE* FTS has taken full spectra of a number of galaxies, including Arp 220 and Mrk 231, revealing the CO rotational ladder (a reliable probe of gas temperature and density) and many lines of water. Initial modelling of the CO spectrum of Mrk 231 shows that both AGN and starburst components are needed, and that the intensities of the CO lines across the *SPIRE* band can be used to estimate accurately the relative magnitudes of the AGN and starburst excitation.

Large-scale surveys of the Milky Way are also a major theme for *Herschel*. Key Projects include Hi-Gal, a five-band survey with *SPIRE–PACS* parallel mode of a ±1-degree strip covering one third of the Galactic plane, detailed surveys of low- and high-mass star-forming clouds, and an investigation of the properties of interstellar dust in all Galactic environments. All of these programmes have returned spectacular initial results, including unprecedented multi-colour images, showing that all of their scientific objectives will be achieved. For instance, initial assessment of an observation of the Aquila field (one of 15 low-mass star-formation regions to be mapped) reveals more than 700 starless cores and 300 young stellar objects. Such data will allow the prestellar core mass function and its relationship with the stellar Initial Mass Function (IMF) to be characterized down to the brown-dwarf limit, and its dependence on environment and cloud properties to be examined in detail.

Herschel is particularly well-adapted to the study of circumstellar material, both matter ejected from evolved stars and the debris discs associated with the forming planetary systems around young stars. Science-demonstration results show the power of *PACS* and *SPIRE* spectroscopy in revealing the properties of the atomic and molecular gas ejected by red supergiants: the two spectrometers together have produced a full spectrum of VY CMa from 55–670 microns, which includes more than 600 spectral lines, and these data are already being compared with models of the chemical and physical conditions in the extended envelope. Photometry of debris discs with *PACS*, spatially resolved for closer objects, has shown that dust masses comparable to that of the Kuiper Belt can be detected.

All three *Herschel* instruments will be used to observe objects in the Solar System, and the early trials show that the planned investigations and more will be feasible. *HIFI* has detected water emission from Comet Garradd. *PACS* and *SPIRE* have made spectral observations of the Martian atmosphere, detecting lines of various isotopes of water, including HDO, and of methane.

A successful test observation of a Kuiper Belt object, Makemake, has been made with *SPIRE*. Since the target is actually fainter (at about 10 mJy), than the extragalactic confusion limit, the measurement required the careful subtraction of two observations made about two days apart, with Makemake in slightly different positions on the sky.

These and many other early *Herschel* results will be published in a special issue of *Astronomy & Astrophysics* in 2010 May. Overall, the observatory is working extremely well. That the early data are of such high quality is attributable not only to the state-of-the-art science payload, but to the enormous preparatory work and effort put into the pre-launch characterization of the instruments and the detailed development and testing of the mission ground segment. *Herschel* will meet or exceed all expectations, and is poised to bring about a revolution in our understanding of the Universe near and far.

The President. These are certainly splendid results — you must be very pleased with it.

Professor Griffin. We are, after the gruelling toil over the years.

Professor F. Taylor. The spectral line of methane on Mars that you showed looked to be of much better quality than anybody else has obtained by any other technique, and this is generating a lot of excitement, of course, because of the biological implications. I just wondered if you knew if there would be more than one line observed and whether anybody has come up with an abundance based on that line.

Professor Griffin. I don't know the answer to either of those questions, but I'm sure people are working on it. You can see the signal-to-noise is good and *PACS* is meeting its specifications so, at least with reasonable integration times and careful treatment of the systematics, it should be able to detect all the lines in the relevant range.

Professor Lynden-Bell. I would just like to say it's a great pleasure to see that an instrument that Peter Fellgett invented in Cambridge many years ago now, the Fourier-transform spectrometer, has produced beautiful results.

Professor Griffin. Indeed. Perhaps I could just make a comment on that: the *SPIRE* FTS is the least popular instrument on *Herschel* because people didn't know what it was and they were a bit worried about it. Even within our own consortium, our own guaranteed time, we had trouble persuading people to use it because they just didn't expect it to be so good. But now we've demonstrated that it does work — and it works beautifully because it is a great concept and in this case it is well adapted to the capabilities of the observatory. We are waging a campaign to popularize it for the second part of the mission.

The President. Thanks, Matt. I'm sure we're all looking forward to many, many more really exciting results. [Applause.] The meeting is now closed; our next meeting is on February 12.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2010 February 12 at $16^h\,00^m$
in the Geological Society Lecture Theatre, Burlington House

A. C. FABIAN, *President*
in the Chair

The President. I am sorry to announce the death of Professor Geoffrey Burbidge FRS of the University of California at La Jolla, San Diego. He died on 2010 January 26, aged 84. He was awarded the Society's Gold Medal for Astronomy in 2005 jointly with his wife Margaret Burbidge FRS. Professor Burbidge was elected a Fellow of the Society on 1948 May 14. His other honours include the Warner Medal, with his wife, in 1959, the Bruce Medal in 1999, and the National Academy of Sciences Award for Scientific Reviewing in 2007. We have also just been notified of the death of Professor Ulrich Schmucker, of Göttingen, Germany, who died on 2008 October 27. He was elected an Honorary Fellow of the Society on 1977 February 11. Could I ask you to stand please? Thank you.

Now on to our programme. I invite Fiorella Lavado and Arthur Miller to talk about 'Weaving the Universe', a talk which accompanies the exhibition in Burlington House.

Professor A. Miller. What precisely a thing called science and a thing called art are have not yet been pinned down. Personally, I have always thought of art–science as a collaboration between an artist and a scientist which produces images that go beyond scientific visualization. Today we are going to explore a particular type of art–science: art–astronomy. Besides radio telescopes and other earthbound instruments, scientists formulate models of the objects in the Universe from data taken by space telescopes such as *Hubble*, which operates at visual wavelengths to give stunning images such as the Eagle Nebula, a star nursery 6500 light-years away. *Chandra* works in the harsh realm of X-rays and γ-rays, and from its data scientists formulate mathematical models of stellar bodies from which artists generate scientific visualizations of what these mysterious objects might look like, and they produce some amazing images of objects which are impossible to perceive, and are enormously far away, such as black holes. What is missing are the visual representations which they evoke and the frightening grandeur and poetry behind them.

Miss Fiorella Lavado. I have read Arthur's book, *The Empire of the Stars*, and other material for information and inspiration. The work has to agree with the scientific narrative but it should also add a layer of artistic imagination. We attend museums and then discuss points of view. He creates the text and I create the artwork and we both participate in this creative process.

Professor Miller. In my book I show how artists can achieve the unimaginable. What is not imaginable is not 'imageable' within the meaning of that term.

Miss Lavado. We wanted to concentrate on imaging black holes, worm holes, and planetary nebulae. I wove these objects manually using stainless steel wire in one continuous piece, and in doing so, they take on a three-dimensional form, as I weave them.

Professor Miller. Black holes can be engines of doom or sources of energy. They can even sing. In 2002 Professor Andy Fabian used data obtained with the *Chandra* telescope to observe the supermassive black hole at the centre of Perseus A. A sonic wave is generated which is pitched at the B flat 57 octaves below middle C on the piano. We cannot see black holes, but consider the view of the white haze at the centre of the Milky Way; in there is the black hole called Sgr A*, possessing three to four million times the mass of the Sun and 23 million kilometres in diameter. The first black hole was discovered in 1972, orbiting the supergiant star HDE 226868 and called Cygnus X-1. Scientists came up with a mathematical model which artists used to create an image. If you look on *Google* you will see an object with an accretion disc 500-km across and an event horizon 42-km across surrounding the black hole. We want to get at the essential grandeur of black holes.

Miss Lavado. To understand the complexity of such an object I reverted to my childhood memories. I grew up on the coast of Peru and the way that the jellyfish float in those waters gave me a clue, so I started weaving the image of a black hole. I wove around me in a sort of rotation. Around this time I was reading science books but I needed to talk to a scientist. I met Arthur and read his book *The Empire of the Stars* and I saw a connection between the energy of a black hole and the energy generated by the clash between Chandrasekhar and Eddington.

Professor Miller. In 1935, A. S. Eddington was one of the world's great astrophysicists and Chandra an unknown 24-year-old scientist, who, five years earlier, had found that in certain circumstance stars can undergo collapse to an infinitesimally small point. When Chandra described this at the RAS on January 11 that year, Eddington, who previously had been a mentor to Chandra, attacked him in such a way that their lives were both altered permanently. In 1972 black holes were discovered, but Chandra never stopped trying to prove that he was a better scientist than Eddington. This story reminds us that science is a human endeavour driven by hopes, dreams, and aspirations, especially at the highest level where people play for the highest stakes.

Miss Lavado. To create a worm hole, I imagine first a spider spinning a web as the image of space with a spider moving along time. By weaving backwards and forwards I created a tunnel. The weaving curve comes back on itself replicating the form of the worm hole.

Professor Miller. A spectacular mode of interstellar travel might be to burrow through the fabric of space-time in a worm hole. Worm holes are tunnels in space-time which allow rapid transit between distant points.

Planetary nebulae consist of a multi-coloured envelope of gas surrounding a cooling core which becomes a white dwarf, a fate that our Sun will meet in about four billion years.

Miss Lavado. How do you weave a nebula? You start from the star in the centre and imagine the layers inside it. A small tool can be used to create the concentrated centre and I was literally dancing to emulate the creation of the planetary nebula. The objects that you will see in the exhibition, the black hole, worm hole, and planetary nebula, are linked not only in the use of material but by a cosmic pattern.

Professor Miller. We combine art and science to explore jointly deep space and time and we look forward to you joining us on this incredible journey. We end with the words of Tom Stoppard, for whom science plays a central rôle in his productions: "Science and Art are nowadays beyond being like each other — sometimes they seem to be each other". Thank you. [Applause.]

Mr. H. Regnart. May I make two comments? Firstly, as a fellow Quaker, Eddington's comments to Chandrasekhar were totally un-Quaker-like. Secondly, the supposed separation of the arts and sciences is one of the most inanely silly modern heresies. To come at a slightly different angle to yourselves, I have sung in the chorus of Haydn's *The Creation* and am reasonably familiar with the score. It begins with a representation of chaos, which predates the

New Viennese School by about a century, but strongly indicates the manner in which randomness may create order. In the section dealing in traditional terms with the creation of the beasts, Haydn accompanies that with the lowest note possible in the orchestra at the time: the B flat below the bass stave played on the contrabassoon.

Professor Miller. But not 57 octaves below [laughter].

Ms. Tracey Olsen. I'm puzzled by the description of black holes which show colours of orange and blue. I thought that it would be white for the heat in the middle.

Professor Miller. All these colours are false colours — there is an arbitrary standard. Usually purple or blue is used for X-ray regions and orange is used for a hot region. I'm bound to say that it's all the same to me as I'm colour blind [laughter].

The President. And often it says, if you look on the web, "artist's conception".

Professor Miller. Right. It's an artist's conception — a scientific visualization, but it does help scientists. From the mathematical model this is what the black hole looks like. In an illustration of the model there is an accretion disc, an event horizon, and so on.

The President. If there are no further questions, thank you again [applause]. The next talk is by Dr. Tim Wright, from Leeds, on 'Fast and furious: witnessing the birth of Africa's new ocean'.

Dr. T. Wright. Atalay Ayele checked the seismic records at the Geophysical Observatory in Addis Ababa University every morning. Often he saw records of distant earthquakes, causing tiny vibrations under Furi Mountain, where the seismometer was located in a deep tunnel away from the noise of regular city life. Occasionally he recognised events that had occurred closer to home — small earthquakes in the Great Rift Valley on faults that were helping his country split apart. But this day was different. The seismic trace, showing the movements of Furi Mountain in the last 24 hours, was surely malfunctioning. Instead of seeing a series of straight lines with occasional wiggles, Atalay saw a mess of angry black lines covering the entire paper sheet — as though a drunken and very hairy caterpillar had gone for a walk on the page. Atalay logged into his computer and went straight to the European–Mediterranean Seismological Centre, which rapidly provides locations for large earthquakes. It was then that he realized something special was happening — a series of earthquakes was striking a remote part of the Afar desert, 500 km to the North, again and again and again. It was 2005 September 21, the first day of the rifting episode.

The Afar depression is a unique place. It sits on the boundary of three tectonic plates, all slowly pulling apart, and is the only place on the planet where the final stages of continental break-up and the initiation of seafloor spreading are happening above sea level. Over the last 30 million years or so, the stretching plates have thinned the Earth's crust, and brought hot material closer to the surface. Flying over the Afar desert today, you see a parched, brown, sandy landscape interrupted only by occasional towering volcanoes and the black basalt that has erupted from them. Coming closer still you see that the basalt is scarred and faulted — tell-tale signs that it is being stretched apart by tectonic forces. Yet most of the time the Earth is quiet, biding its time. The region is slowly stretching, at about the speed your fingernails grow, but, like an elastic band, eventually something has to break. In ten days at the end of 2005 September, the boundary between the African and Arabian plates broke. Along a 60-km section, the two plates moved apart by up to 8 metres. This was accompanied by the injection of 2·5 cubic kilometres of molten rock into the crack between the plates — enough rock to deposit a metre-thick blanket on London and the area within the M25. Surface faults moved by several metres, fissures opened up that swallowed camels, and a small eruption turned the sky black for 3 days. The local people were understandably terrified. Four years later, the rifting episode has slowed down, but shows no imminent signs of stopping.

I am leading an international consortium of scientists who were invited by Addis Ababa University and the Ethiopian Government to investigate what is happening in Afar. We have installed sensitive seismometers and GPS instruments on the ground near the rift, and are monitoring with satellites how the ground moves. At the same time, we are analysing rocks erupted in the past so we can understand how the system has behaved previously and what may happen in the future, and we are probing deep into the Earth's crust with geophysical methods to locate pockets of molten rock in the crust. Our seismometers even let us see deeper within the Earth, and we have identified hot material rising deep beneath Afar that may be the ultimate cause of the crisis at the surface. What has become clear during the last 4 years is that these events are rare. There are no records or accounts of anything on this scale having occurred in Afar in living memory, and it is likely that such an episode occurs here only once every 500 years or so. Above sea level, this is the first rifting episode to have been seen since an event in Iceland in the 1970s, and it is the first that we have been able to monitor with modern scientific instruments.

So why are we interested? Seventy percent of our planet's surface is made where tectonic plates pull apart, at mid-ocean ridges. Yet observations of how that actually happens are extremely difficult to make under several kilometres of water, where 99% of the ridges lie. In Afar, we can monitor the activity with satellites, place instruments on the ground, and analyse rocks associated with known eruptions. Using satellite radar interferometry, we can build up detailed time-series of how the ground deforms. This has revealed the response of the Earth to the initial event, and it has particularly shown us how complex the magma plumbing system of the rift is — there are several shallow magma chambers that have been refilling slowly since the initial activity, and magma seems to be flowing at depth for many kilometres towards the rift axis. Furthermore, a series of new magmatic intrusions continue to hit the rift every few months.

We are gathering information on Afar that is crucial for understanding how our planet is shaped, and how major oceans such as the Atlantic are born. Our research confirms that we seem to be witnessing the birth of a new ocean in Ethiopia — caused by a deep hot spot rising from the Earth's core. But don't invest in beach-front property just yet — it may be a million years or so before the water floods in.

Mr. M. Kent. At what altitude is the rift occurring in the desert?

Dr. Wright. It varies along the rift segment but the centre of it is about 800 metres above sea level. Some of the volcanoes go up to 1400 metres and the lowest parts are at 400 metres. If you go further north along the axis you get to parts which are as much as 100 metres below sea level.

Mr. M. Britten. Are these techniques being used around the Vesuvius region?

Dr. Wright. They are, yes, but Vesuvius itself is not deforming very much — it's usually the areas away from the volcano that are more interesting. In the Campi Flegrei region to the NW of Vesuvius the area is deforming a lot — the Romans even knew about it.

Professor D. Kurtz. Following on from your title, when does the waterfall begin to fill the ocean?

Dr. Wright. Let me show you a little map.

Professor Kurtz. You were ready for that question!

Dr. Wright. I was, yes! [Laughter.] I don't have a nice movie here but we are preparing an animation for an exhibition which we are doing at the Summer Exhibition of the Royal Society. There is a barrier some 25 metres high here on the border in Eritrea, which is all that is stopping the coast from coming in to the area below sea level. Eventually the whole of the Horn of Africa will split off. That's happening fairly slowly or it may stall. There are plenty of examples of slow rifts that just stop. This one in Afar has gone too far to stall and when it breaks apart water is going to flood in through Eritrea. If you came back in a million years or so I would be very surprised if there wasn't a lot of water in there.

Professor Kurtz. With only a 25-metre drop is there any chance you could utilize hydroelectric power?

Dr. Wright. The basin is big enough. You could probably arrange to do it at the right rate so that the water evaporated in the heat. The real challenge would be to get co-operation between Ethiopia and Eritrea.

Mr. N. Calder. Do you have a ball-park figure for the energy involved in this event?

Dr. Wright. It's about the equivalent of a magnitude 7·5 earthquake. The United States Geological Survey has a website which contains tables allowing you to convert between the size of earthquakes and energy in various units.

Mr. M. F. Osmaston. Do you have any measures for the Danakil block?

Dr. Wright. We are monitoring the entire area. Everything in this region is moving faster than it was and it has had a kick from this event. What we think is happening is that the lower crust and mantle are flowing in response, and this is then coupled to the upper crust, so everything is stretching faster than it would be otherwise. We have no direct measures of the Danakil block apart from space observations, because it is mostly in Eritrea.

Mr. Osmaston. Is there any longer-timescale movement?

Dr. Wright. It appears to be rotating. One end is pinned to the Nubian plate and the other end is pinned to the Arabian plate. This is still a model and there is no direct evidence.

Professor P. G. Murdin. The reason I'm standing up here is because I am chairing the second half of this meeting. It's that time of the year when our President gives us his Presidential Address and so I will ask Andy to talk about 'The impact of astronomy'.

The President. [A summary of this talk has appeared in *Astronomy & Geophysics*, **51**, 25, 2010.]

Professor Murdin. Thank you very much, Andy. We have some time for discussion.

Professor M. A. Barstow. I'd like to add one thing to your list at the end. Notwithstanding the financial problems we have at the moment, which are clearly substantial, I think that the funding process has done something to us over a long period of time irrespective of the amount of money: it has squeezed out quite a lot of the innovation, and is one of the reasons we had so much 'bang for our buck', particularly when we worked in international collaborations in the late seventies and eighties, which is something that we have lost over the last couple of decades. Somehow, within this current funding crisis, we need to reinvent some of that drive, so that when we come out of the present situation we have those new ideas or devices that can keep us at the table.

The President. I completely agree.

Professor I. Roxburgh. I'd like to take issue with something you said.

The President. I thought that somebody would [laughter].

Professor Roxburgh. It isn't the size of the group that matters, it's the quality of the work that they do, so concentrating on projects significantly above a critical mass is not to me a criterion. We should be concentrating support on the best-quality research.

Dr. A. Chapman. One interesting point historically is that astronomy is not the oldest of the sciences but it's the oldest one that is 'mathematizable'. It was also the first one that was instrumental and from Greek times onwards formed the model of how one may inquire into the Universe or the natural world. It's not until organic chemistry at the beginning of the 19th Century that there appears another science (with the exception of experimental physics) that is susceptible to mathematical, cross-checking, hypothesis-predicted treatment. Compared with 19th-Century medicine, astronomy was far in advance in practical matters.

The President. Thank you very much, Allan, I'll try and encapsulate that in my write-up.

Professor M. Rowan-Robinson. Some years ago, I tried to summarize examples of economic impact. You have found some very nice additional examples. I think that these do matter, and I think you are saying that the Government does not think this way, but this kind of thinking is deeply ingrained in the Treasury. There was a recent court case involving the Wi-Fi patent in which big industry was made to pay money because they decided that the radio astronomers really did discover the technique. Another example is the sub-mm technology used at airports that resulted from a planetary-imaging device. Even the Treasury picked that up two or three years ago. These examples are important. The challenge would be to try looking at your own papers for examples of economic impact.

Professor Murdin. Alan Watson provided an example a year ago in relation to the *Auger* detectors and their networking capability.

Professor Rowan-Robinson. I think the RAS should produce a dossier of all these examples and you can then cite that.

The President. We are trying to do so.

Professor Rowan-Robinson. I can't prove that my own work has had fallout or impact but I can be sure that past work did have impact.

Professor D. Lynden-Bell. I do hope that this is not the new dodgy dossier! [Laughter.]

The President. I hope that anyone here who knows any good stories will email me. I agree with you that we need to pile them up and push them forward, but at the same time we have to put the case for what we do and the way we do it.

Professor Murdin. We are now in negative time. I'll take two more questions.

Rev. G. Barber. Returning to the first talk we had this evening about the relation between art and science, with your example on outreach to the general public, you need to understand that there is also rejection of science (*a*) because at school it is seems a hard option and (*b*) you don't want to be seen as a nerd; but I think astronomy has a reputation which means you can sell it to people.

The President. I'm told that GCSE Astronomy appeals more than Physics to girls. It's a strong argument for us doing what we can.

Mr. C. E. Barclay. You've alluded to the long-standing interest in astronomy and I know from my school experience that there are few pupils aged 11 who are not interested in either astronomy or dinosaurs. The interest is there but what then happens is that the system has taken root such that the nerd sets in and switch-off comes along. The drive needs to be there earlier to catch people.

The future of scientific success depends on them not being put off and astronomy has a really big rôle to play.

The President. I agree with you. Thanks for emphasizing it from your perspective.

Professor Murdin. It's time to finish and we should thank the President for his address [applause].

The President. The wine reception will be held in the Society's apartments and on the way you can pass the exhibition described earlier. The next meeting will be on Friday, March 12.

PHOTOGRAPHIC COUDÉ RADIAL VELOCITIES OF STANDARD-VELOCITY STARS

By C. D. Scarfe
University of Victoria

Twenty years ago Scarfe *et al.*[1] published radial velocities of some of the IAU standard-velocity stars tabulated by Pearce[2]. This paper provides additional data, and extends the number of stars for which the data are numerous enough to provide reliable average values.

Introduction

The standard-velocity-star system adopted by the IAU[2] is now over fifty years old, and in its original form is insufficiently precise for many modern applications. However, in 1990 Scarfe *et al.*[1] (henceforth SBF) showed that at least some of the stars in that list were constant at the level of 0·20 km s^{-1} or less, adequate for all studies but those of the highest precision. A summary of their results, along with some basic data for the stars, is presented in Table I. The mean velocities they obtained were the most precise that had been obtained of those stars up to that date. As Table I shows, they agreed fairly well with those of the IAU list in many cases but differed significantly in others. However, the number of observations of any particular star exceeded ten for only six stars, all of them in the 'Bright' list of Pearce[2]. Moreover, for only four of them (β Gem, β Vir, α Boo, and ι Psc) had the data been obtained over a period exceeding ten years. The individual standard deviations of a single observation from the mean were all about 0·20 km s^{-1} or less, but in the case of four stars, marked in Table I with asterisks, that had been achieved by excluding one discordant observation of each star. This paper's purpose is to increase the number of stars with standard deviations in the same range, over an interval of at least ten years, with at least ten observations of each star, and so to enlarge the sample of well-determined radial velocities known to be constant at the above level.

TABLE I

Basic properties of the stars and summary of earlier (SBF) work

Star	*HR*	*HD*	*Sp. Type*	V_{IAU} *km s⁻¹*	*No. Obs.*	*Int. days*	*Mean V km s⁻¹*	*S.D.*[a] *km s⁻¹*	*S.D. of M. km s⁻¹*
				a. IAU 'Bright' Stars					
α Cas	168	3712	K0 III	−3·9	8	3268	−4·26	0·10	0·04
β Cet	188	4128	K1 III	13·1	1		13·16		
α Ari	617	12929	K2 III	−14·3	14	2978	−14·51	0·11	0·04
α Cet	911	18884	M1·5 III	−25·8	3*	905	−25·30	0·20	0·10
α Tau	1457	29139	K5 III	54·1	5	2365	54·25	0·08	0·03
β Gem	2990	62509	K0 III	3·3	28	4473	3·23	0·14	0·03
α Hya	3748	81797	K3 II–III	−4·4	6	7238	−4·35	0·19	0·08
ε Leo	3873	84441	G1 II	4·8	6	3476	4·40	0·08	0·03
β Vir	4540	102870	F9 V	5·0	15	6860	4·38	0·11	0·03
α Boo	5340	124897	K2 IIIp	−5·3	11	4368	−5·30	0·12	0·04
δ Oph	6056	146051	M0·5 III	−19·8	5	700	−19·14	0·20	0·09
α Her	6406	156014	M5 Ib–II	−32·5	0				
β Oph	6603	161096	K2 III	−12·0	19	2579	−12·18	0·13	0·03
γ Aql	7525	186791	K3 II	−2·1	4*	2543	−1·97	0·11	0·06
β Aqr	8232	204867	G0 Ib	6·7	8	2579	6·71	0·20	0·07
ε Peg	8308	206778	K2 Ib	5·2	0				
ι Psc	8969	222368	F7 V	5·3	22	5080	5·60	0·16	0·03
				b. IAU 'Faint' Stars					
6 Cet	33	693	F5 V	14·7	1		15·09		
10 Tau	1101	22484	F8 V	27·9	5	2302	27·95	0·19	0·08
43 Tau	1283	26162	K2 III	23·9	1		24·79		
	3145	66141	K2 III	70·9	7	2924	71·45	0·17	0·06
40 Leo	4054	89449	F6 IV	6·5	4*	2525	6·43	0·18	0·09
	4550	103095	G8 Vp	−99·1	2	3661	−98·58	0·12	0·08
16 Vir	4695	107328	K1 III	35·7	2	15	36·48	0·04	0·03
σ Vir	5015	115521	M2 III	−26·8	1		−27·28		
5 Ser	5694	136202	F8 IV–V	53·5	7*	1153	54·45	0·15	0·06
κ Her	6008	145001	G8 III	−9·5	1		−10·33		
	6349	154417	F8 IV–V	−17·4	1		−16·92		
31 Aql	7373	182572	G8 IV	−100·5	6	1102	−100·27	0·21	0·09
ο Aql	7560	187691	F8 V	0·1	1		−0·05		
35 Peg	8551	212943	K0 III–IV	54·3	2	801	54·26	0·04	0·03

[a] The larger of the internal and external standard deviations.
* One observation omitted from mean and S.D.

New observations

Following the publication of SBF, an effort was made to obtain photographic spectra of additional standards, while plates remained available. The equipment used remained as described in SBF, as well as the exposure and development procedures. The plates were measured with the *ARCTURUS* oscilloscopic measuring machine; the lines chosen for measurement were the same as had been used for SBF. Most of the plates were taken prior to 1996, and those were measured before the measuring machine was decommissioned, in 1999. A few plates taken later in the 1990s remain unmeasured, but plates were no longer used after 1999. The total number of additional measured plates is 150, of which 131 were obtained and measured by the author, and 19 by A. H. Batten. The new velocities are listed in Table II. Together with those published in SBF, they bring the total for IAU standards to 347, an increase of 75%.

TABLE II

Individual radial velocities obtained since 1990 paper

Date[a]	*km s*$^{-1}$	*Date*[a]	*km s*$^{-1}$	*Date*[a]	*km s*$^{-1}$
β Oph		δ Oph		γ Aql	
7792·63	−12·18	7942·07	−19·14	7815·66	−3·05
7999·94	−12·34	8081·73	−19·23	8081·87	−2·87
8108·73	−12·08	8105·78	−18·84*	8440·88	−2·77
8112·71	−12·02*	8158·66	−19·25	8747·01	−2·81
8440·82	−12·08	8440·74	−19·56	9132·96	−3·14
8514·63	−12·21	8691·03	−19·21	9241·78	−2·92
8746·93	−12·31	8818·72	−19·69	9264·69	−3·14
8804·84	−12·12	9037·09	−19·77	9540·90	−2·47
9074·06	−12·32	9205·72	−19·61	9915·80	−2·91
9132·89	−12·22	9540·73	−19·46		
9540·79	−12·38				
9915·72	−12·22				
α Tau		ι Psc		5 Ser	
8159·06	54·37	7792·82	5·58	7987·94	54·28*
8325·62	54·26	8081·96	5·81	8021·80	54·59*
8515·06	54·05	8088·86	5·87*	8278·07	54·46
8613·83	53·85	8108·97	5·56	8358·84	54·36*
8690·61	54·21	8514·84	5·66	8371·85	54·66*
9036·70	54·45	9206·00	5·70	8746·88	54·38
9230·05	54·26	9246·81	5·57	8777·75	54·52*
9383·57	53·96	9562·99	5·57	9830·89	54·46
9739·71	54·18				
α Cas		α Ari		10 Tau	
7871·69	−4·22	7815·79	−14·50	7792·92	27·95
8082·00	−4·07	8109·00	−14·51	7941·61	28·18
8277·57	−4·46	8277·60	−14·50	8112·98	28·04*
8819·00	−4·28	9036·58	−14·00	8158·94	28·14
9241·91	−4·12	9246·92	−14·52	8513·90	28·66*
9614·96	−4·38	9358·67	−14·55	9264·95	27·88
9739·61	−4·24	9739·60	−14·67	9739·67	28·04
β Gem		β Vir		α Cet	
7816·07	3·36	7941·97	4·38	7792·89	−26·18
7999·66	3·44	8278·01	4·49	8105·97	−25·49*
8159·06	3·34	8372·78	4·48	8109·01	−26·00
8325·72	3·32	8690·93	4·31	8127·92	−25·37*
9036·90	3·42	9036·98	4·45	8526·84	−26·15*
9304·10	3·34	9830·77	4·25	9229·95	−26·02
α Boo		β Aqr		β Cet	
7942·02	−5·11	8081·93	6·86	7792·87	13·12
8278·13	−5·43	8082·89	6·90*	8081·98	13·31
8691·09	−5·12	8105·85	6·56*	8514·87	13·11
9037·03	−5·36	8805·01	7·05	9229·93	12·91
9132·82	−5·48	9229·81	6·58	9563·02	13·21
9831·04	−5·49	9540·99	6·60		
ε Leo		o Aql		α Hya	
8372·69	4·41	8108·82	0·10	7941·84	−4·11
8690·38	4·42	8514·71	−0·16	8277·94	−4·41
9082·73	4·39	9205·86	−0·19	8690·82	−4·40
9418·68	4·32	9246·74	0·14	9358·97	−4·62
9830·69	4·44	9562·87	−0·14		

TABLE II (*concluded*)

Date[a]	*km s*$^{-1}$	*Date*[a]	*km s*$^{-1}$	*Date*[a]	*km s*$^{-1}$
α Her		HR 3145		31 Aql	
9073·99	−34·17	7941·75	71·80	8081·81	−100·15
9229·66	−33·00	8277·85	71·77	8818·78	−100·20
9264·62	−33·62	8358·72	72·13*	9229·75	−100·30
9562·73	−34·69	9383·82	71·87	9614·72	−100·25
35 Peg		6 Cet		40 Leo	
7792·76	54·30	8105·89	15·07*	8325·80	6·11
8158·80	54·47	8112·92	14·94*	9383·93	5·74
8818·95	54·30	8127·88	15·07*		
9229·88	54·36				
16 Vir		κ Her		ε Peg	
8746·78	36·37	8804·78	10·00	9264·79	3·95

[a] Julian Date − 2440000.
*Observed and measured by A. H. Batten.

Results

Table III gives mean values and standard deviations of individual observations and of the mean for the data of SBF combined with those presented in Table II, including those omitted from the statistics of SBF. In three of those cases, the M-type giant α Cet, the bright giant γ Aql, and the broad-lined dwarf 40 Leo, the new data agree fairly well with the previously discarded observation, or fill the gap between it and the other data of SBF. For those objects, not surprisingly, the standard deviation has increased considerably from Table I to Table III. In the other case, 5 Ser, the discrepant plate was a weak exposure, which yielded on re-measurement a result more consistent with the other data for the star.

As can be seen in Table III, the number of IAU 'Bright' standards for which at least ten observations, spread over at least 10 years, with a standard deviation no larger than 0·20 km s^{-1}, has increased from four to eleven, with one additional promising candidate in β Cet, whose southerly declination has meant that the number of observations is too few and the elapsed time too short. Observations of the M0·5III star δ Oph show a scatter somewhat over the above limit, and this trend to larger scatter with later type appears to continue with α Cet, M1·5 III, and α Her, M5 Ib–II. The latter star is of course also very luminous, with a surface gravity probably even lower than that of the M giants, so its instability is not surprising. With that in mind, we suspect that had further observations of ε Peg been obtained, they would have shown a fairly large scatter. However, ε Leo and β Aqr, which are luminous but of earlier type, do not. None of the very cool stars can be regarded as a high-quality standard, but perhaps δ Oph and possibly also α Cet could be retained for use with stars of similar type. It should be noted, however, that for α Cet and γ Aql the new result differs substantially from that of SBF, for reasons given in the preceding paragraph, and even δ Oph now gives a result that differs from the previous one by about twice the standard deviation of the mean value.

The results for IAU 'Faint' stars are less satisfactory. Only 5 Ser satisfies the above criteria, although 31 Aql fails only on the span of time. Both 10 Tau and HR 3145 show standard deviations slightly larger than 0·20 km s^{-1}, while for 6 Cet, *o* Aql, and HR 3145 there are still too few data over too short a time interval. For HR 4550, 16 Vir, and κ Her the time interval is long enough,

TABLE III

New results

Star	*No. Obs.*	*Interval (days)*	*Mean V. (km s^{-1})*	*S.D. (km s^{-1})*	*S.D. of M. (km s^{-1})*	*$V-V_{IAU}$ (km s^{-1})*	*$V-V_{SBF}$ (km s^{-1})*
			a. IAU 'Bright' Stars				
α Cas	15	5289	−4·26	0·11	0·03	−0·36	0·00
β Cet	6	1844	13·14	0·13	0·05	0·04	−0·02
α Ari	21	5289	−14·49	0·15	0·03	−0·19	0·02
α Cet	9	3667	−25·76	0·39	0·13	0·04	−0·46
α Tau	14	4520	54·20	0·16	0·04	0·10	−0·05
β Gem	34	6193	3·26	0·14	0·02	−0·04	0·03
α Hya	10	9013	−4·36	0·19	0·06	0·04	−0·01
ε Leo	11	9481	4·40	0·05	0·02	−0·40	0·00
β Vir	21	9472	4·38	0·11	0·02	−0·62	0·00
α Boo	17	6615	−5·31	0·14	0·03	−0·01	−0·01
δ Oph	15	3275	−19·30	0·28	0·07	0·50	−0·16
α Her	4	489	−33·87	0·73	0·36	−1·37	
β Oph	31	4776	−12·19	0·13	0·02	−0·19	−0·01
γ Aql	13	6982	−2·70	0·46	0·13	−0·60	−0·73
β Aqr	14	4401	6·73	0·18	0·05	0·03	0·02
ε Peg	1		3·95			−1·25	
ι Psc	30	6924	5·62	0·15	0·03	0·32	0·02
			b. IAU 'Faint' Stars				
6 Cet	4	1099	15·04	0·07	0·03	0·34	−0·05
10 Tau	12	5572	28·05	0·24	0·07	0·15	0·10
43 Tau	1		24·79			0·89	
HR 3145	11	5817	71·61	0·27	0·08	0·71	0·16
40 Leo	7	5817	6·29	0·29	0·11	−0·21	−0·14
HR 4550	2	3661	−98·58	0·12	0·08	0·52	
16 Vir	3	5180	36·44	0·06	0·04	0·74	−0·04
σ Vir	1		−27·28			−0·48	
5 Ser	15	4402	54·44	0·15	0·04	0·94	−0·01
κ Her	2	4789	−10·16	0·23	0·16	−0·66	0·17
HR 6349	1		−16·92			0·48	
31 Aql	10	2985	−100·25	0·16	0·05	0·25	0·02
o Aql	6	1844	−0·05	0·14	0·06	−0·15	0·00
35 Peg	6	2941	54·33	0·08	0·03	0·03	0·07

but the number of observations is still far too few to give a plausible result. As mentioned above, the lines in the spectrum of 40 Leo are broadened, presumably by rotation, and the scatter of the data is unlikely to be reduced by additional observations. For 43 Tau, HR 6349, and σ Vir we still have only one observation. However, the last of these has been found[3,4] to be variable over several km s^{-1}, and may be a double or multiple system.

The observations show consistency over time, as can be seen from Figs. 1 to 5, in which residuals from the mean values for several stars are plotted against the Julian date. Comparison of Figs. 1 and 2 shows that the scatter for K giants at this level of precision is in general no larger than that for F and G dwarfs. It should perhaps be noted that a few stars show some apparent systematic trends that are masked by combining the data from stars of similar type, as has been done here. For example, β Gem and HR 3145 show rather similar trends, as Fig. 3 reveals. It is impossible to decide from these data whether those apparent trends represent some real variation, similar to that first found by Walker *et al.*[5] for some of the giant stars observed for this paper, because even if no attempt is made to remove the trends by arbitrarily fitting a straight line

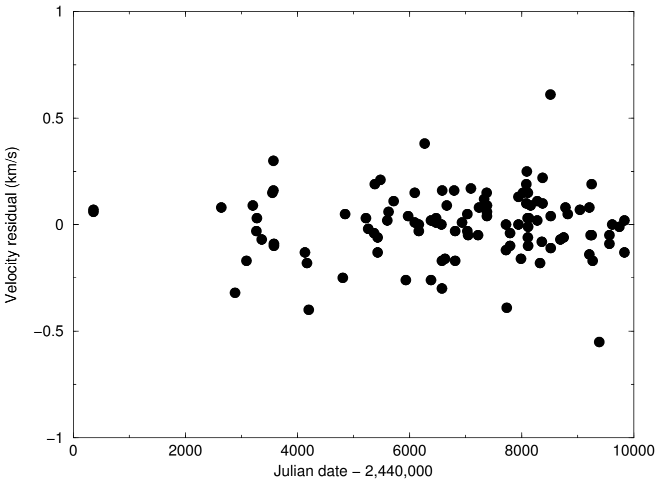

FIG. 1

The residuals from each star's mean velocity plotted against the Julian Date, for the dwarf stars ι Psc, β Vir, 5 Ser, 10 Tau, 40 Leo, *o* Aql, 6 Cet, and HR 4550, and the subgiant 31 Aql.

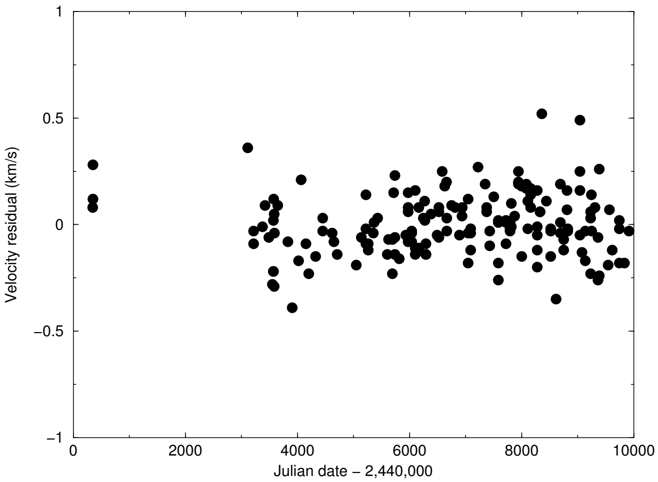

FIG. 2

The same as Fig. 1, but for the K giants β Gem, β Oph, α Ari, α Boo, α Cas, α Tau, α Hya, β Cet, HR 3145, 35 Peg, 16 Vir, and κ Her.

to the data, the scatter for those stars is similar to that for other giants. The apparent variation for β Gem bears no resemblance to that found recently by Reffert *et al.*[6], and attributed to orbital motion; the amplitude of that motion is too small to be detected here. Fig. 4 shows the slightly larger scatter of data for the two M giants, which renders the apparent trend unlikely to be real. Fig. 5,

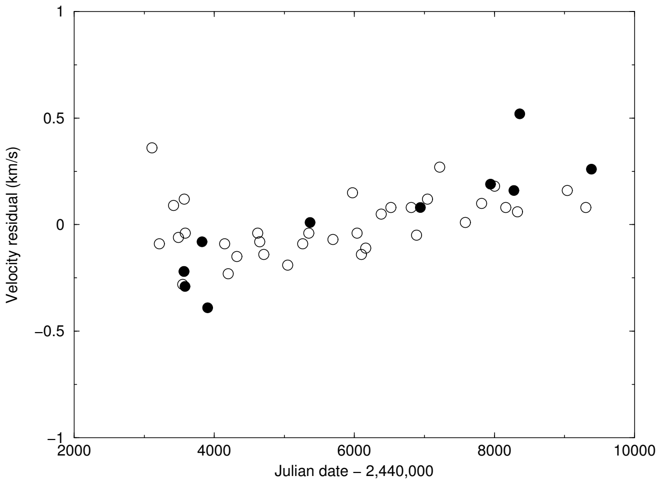

FIG. 3
The same as Fig. 1, for the K giants β Gem (open circles) and HR 3145 (filled circles) separately.

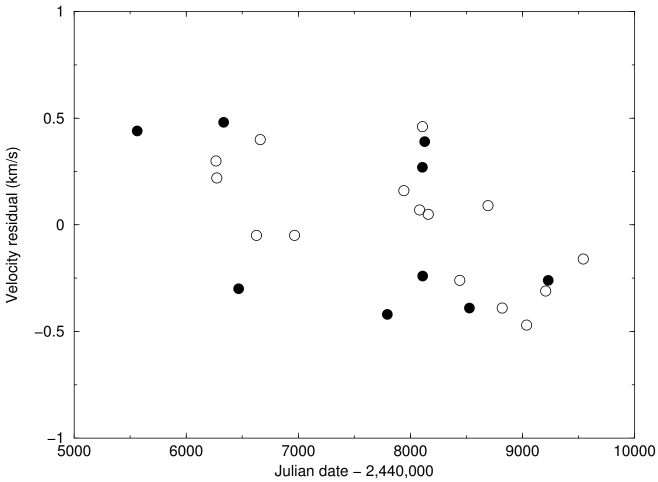

FIG. 4
The same as Fig. 1, but for the M giants α Hya (filled circles) and δ Oph (open circles).

in which residuals for individual stars are plotted, shows the increase in scatter with decreasing temperature for stars more luminous than ordinary giants, and suggests that those stars may be intrinsically variable, as has been found by others using more precise techniques.

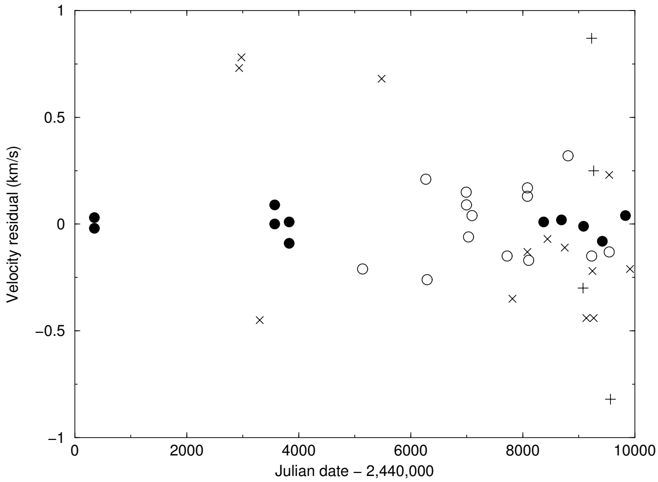

FIG. 5

The same as Fig. 1, but for bright giants and supergiants: filled circles — ε Leo (G1 II), open circles — β Aqr (G0 Ib), crosses — γ Aql (K3 II), plus signs — α Her (M5 Ib−II).

Comparison with other work

A systematic difference, which increased with decreasing temperature from nearly zero for stars like the Sun to about 1·0 km s^{-1} for M-type giants, was found by SBF between their data and those obtained[7] with the *Coravel*[8] spectrometer. A similar trend was also found[9] by the group at the Center for Astrophysics, between their data and those from *Coravel*, as a function of $B - V$ colour index, instead of spectral type. But careful comparison revealed no such colour dependence between CfA and DAO data.

More recently the *Coravel* group have developed the *Elodie* spectrometer[10], and used it to determine corrections to the *Coravel* velocities, a new list of which has been published[11]. The CfA results have also now been published[12]. Those results for the stars of this paper are presented in Table IV, and the differences between them and the present results are plotted against $B - V$ in Figs. 6 and 7. Fig. 8 shows the differences, listed in Table III, between the present results and the IAU[2] standard velocities, also as a function of $B - V$.

There is no significant dependence on colour in any of Figs. 6, 7, and 8. However, the range of values in Fig. 8 is considerably larger than in Figs. 6 and 7, indicating better agreement between all the three modern data sets than between them and the older IAU values.

More recently Nidever *et al.*[13] published an extensive set of high-quality radial-velocity measurements of bright stars. Unfortunately there are only six stars in common between their list and Table III, and for two of them the results of Table III are uncertain because there are only one or two observations. However, for the other four, β Vir, ι Psc, 10 Tau, and 31 Aql, the agreement is excellent, being roughly equal to the standard deviations of our mean values, listed in the sixth column of Table III. This suggests that our zero-point is the same as theirs.

TABLE IV

Comparison with other work

Star	*B − V*	*DAO* km s⁻¹	*COR* km s⁻¹	*DAO − COR* km s⁻¹	*CfA* km s⁻¹	*DAO − CfA* km s⁻¹
			a. IAU 'Bright' Stars			
α Cas	1·17	−4·26	−4·3	0·04		
β Cet	1·02	13·14	13·1	0·04	13·25	−0·11
α Ari	1·15	−14·49	−14·6	0·11	−14·48	−0·01
α Cet[a]	1·63	−25·76	−26·1	0·34	−25·57	−0·19
α Tau	1·54	54·20	54·2	0·00	54·15	0·05
β Gem	0·99	3·26	3·2	0·06	3·26	0·00
α Hya	1·44	−4·36	−4·7	0·34	−4·38	0·02
ε Leo	0·81	4·40	4·5	−0·10		
β Vir	0·52	4·38	4·3	0·08	4·38	0·00
α Boo	1·24	−5·31	−5·3	−0·01	−5·14	−0·17
δ Oph[a]	1·58	−19·30	−19·6	0·30	−19·30	0·00
α Her[b]	1·44	−33·87	−32·0	−1·87	−30·24	−3·63
β Oph	1·17	−12·19	−12·5	0·31	−12·29	0·10
γ Aql[a]	1·51	−2·70	−2·8	0·10		
β Aqr	0·83	6·73	6·3	0·43	6·36	0·37
ε Peg[a]	1·52	3·95	3·4	0·55	3·61	0·34
ι Psc	0·51	5·62	5·6	0·02	5·47	0·15
			b. IAU 'Faint' Stars			
6 Cet	0·49	15·04	15·0	0·04	14·50	0·54
10 Tau	0·57	28·05	27·9	0·15	27·92	0·13
43 Tau[a]	1·08	24·79	24·8	−0·01	24·77	0·02
HR 3145	1·25	71·61	71·6	0·01	71·74	−0·13
40 Leo	0·45	6·29	6·3	−0·01	5·98	0·31
HR 4550[a]	0·75	−98·58	−98·3	−0·28	−98·21	−0·37
16 Vir	1·17	36·44	36·4	0·04	36·53	−0·09
σ Vir[b]	1·64	−27·28	−28·6	1·32	−29·20	1·92
5 Ser	0·54	54·44	54·3	0·14	54·35	0·09
κ Her[a]	0·93	−10·16	−10·3	0·14	−10·39	0·23
HR 6349[a]	0·58	−16·92	−16·8	−0·12	−16·89	−0·03
31 Aql	0·76	−100·25	−100·4	0·15	−100·22	−0·03
ο Aql	0·56	−0·05	0·0	−0·05	0·04	−0·09
35 Peg	1·04	54·33	54·2	0·13	54·22	0·11

[a]Present result uncertain — large scatter or few observations.
[b]All results uncertain — velocity probably variable.

Conclusion

This paper presents the bulk of the additional photographic observations of IAU standards obtained since the publication of SBF. Until such time as a suitable measuring machine becomes available, the remainder of the plates will remain unmeasured. However, their number is not so large as to make likely any significant change in the results of this paper.

The colour-dependent discrepancy between DAO and *Coravel* results has been removed, as a result of revisions made possible by the use of *Elodie*[9]. There may be a small zero-point difference between our results and those from *Coravel* and from CfA, but we leave that for now. Over a period that substantially overlaps that covered by the present data and those of SBF, observations of IAU standard stars have been obtained by the author with the DAO radial-velocity spectrometer (*RVS*). Those data include almost all of the standards that are accessible from Victoria, and are much more numerous, but less precise, than the data presented here. In addition, the *RVS* has been used to obtain well over 100 observations of asteroids, whose velocities can be readily calculated from

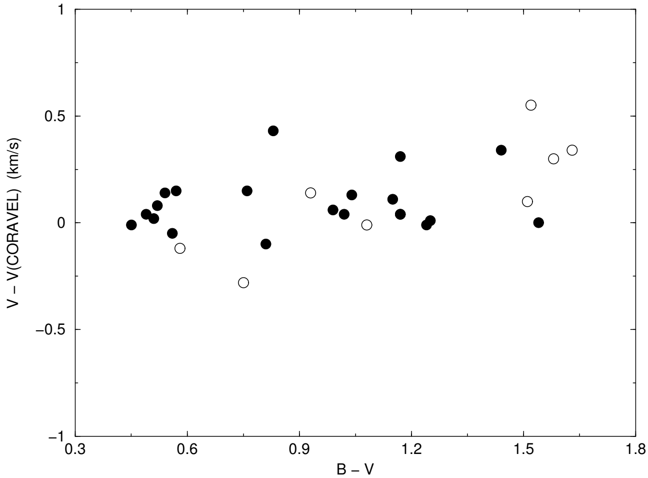

FIG. 6

The difference between DAO and *Coravel* velocities plotted against $B - V$ colour index. Filled circles represent the most reliable results, and open circles those for which the DAO data are less certain, denoted by superscript '*a*' in Table IV. The two objects that are probably variable (superscript '*b*' in Table IV) are off-scale in this figure.

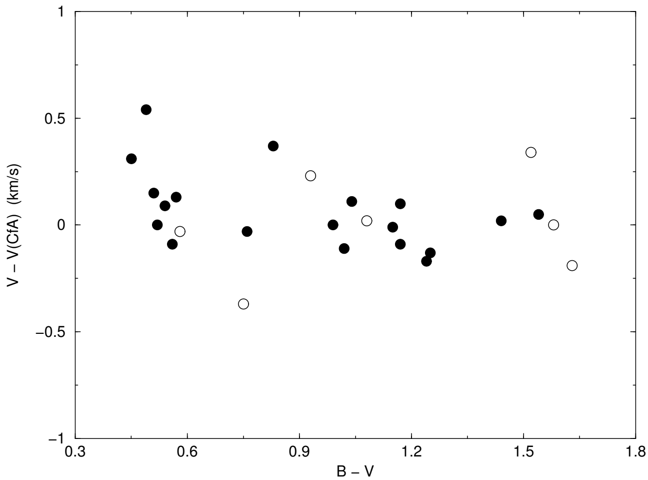

FIG. 7

The same as Fig. 6, but for the difference between DAO and CfA velocities.

their orbits. Those data permit a reliable determination of the zero-point of the *RVS* system. Full discussions of the stellar and asteroid data, including a tie-in to the data of this paper and a discussion of zero-point differences between systems, will be the subject of one or more future papers.

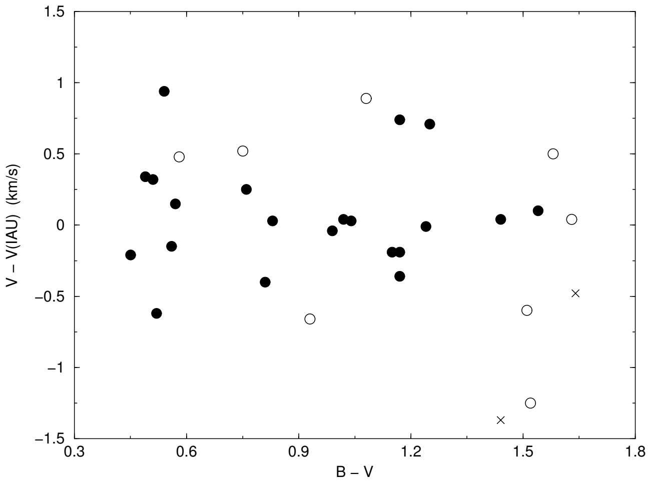

FIG. 8

The same as Fig. 6, but for the difference between DAO and IAU velocities. The two objects denoted with superscript '*b*' in Table IV are included as crosses. Note the larger range of the vertical scale compared with those of Figs. 6 and 7.

Acknowledgements

I am grateful to A. H. Batten for his interest in, and support of, this work, exhibited by his obtaining some of the new data, as indicated in Table II. I very much appreciate the granting, by the National Research Council of Canada, of Guest Worker status and of the opportunity to use the 1·2-m telescope and its *McKellar* spectrograph, as well as the measuring machine and computer, that this status provides. I also wish to thank the referee, Roger Griffin, for several helpful suggestions. The work was supported in part by grants from the Natural Sciences and Engineering Research Council of Canada, and from the University of Victoria.

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PERIODIC BEHAVIOUR OF STARS IN THE GEOS RR LYRAE DATABASE

PAPER 3: EF CANCRI AND BD DRACONIS

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The GEOS values for the times of maximum light have been investigated for the RR Lyrae stars EF Cancri and BD Draconis. Both are shown to have longer periods in addition to their pulsation periods. The data for EF Cnc are insufficient to determine which of three possible periods is the definitive one, but a period of near to 11 days is currently the most likely. The O – C values folded with this period show a continuous sine-like curve with a total range of about 0·025 days. BD Dra has changed its pulsation period at least three times over the last 110 years. Additionally it has a very definite period of near to 24 days, clearly visible in the more-recent observations. The data folded with this period show a continuous variation with a broad maximum and a short and deep minimum. The total range of this variation is about 0·08 days. The shape of this variation is what one might expect to be due to light-travel times from a star in an eccentric binary orbit, but the combination of a 24-day period with a total amplitude of 0·08 days is not compatible with a simple binary model. In both cases the phase diagrams have very different characteristics to those of the stars RR Lyr and AR Her discussed earlier in this series of papers. If the variations in both RR Lyr and AR Her are Blazhko-effect-type variations then the question arises as to what is the source of the variations in EF Cnc and BD Dra. If they are Blazhko-type variations then some explanation has to be found for the very different shapes of the variations. If they are not Blazhko-type variations then their source needs to be discovered.

Introduction

This paper continues the periodic analysis of stars in the GEOS database of O – C values for RR Lyrae stars that have O – C diagrams which indicate that the periods can be improved and that there might be secondary periods present. EF Cancri and BD Draconis both had listed periods which could be improved. The periods have been modified and the corrected O – C values for both stars have been analysed for secondary periods in order to search for Blazhko-type variations. The stars are treated together as both stars are found to have secondary periods, 11 days and 24 days, respectively. In both cases the resultant phase diagrams show continuous variations over the secondary period, a very different result from that found for RR Lyr in Paper 1[1] and AR Her in Paper 2[2].

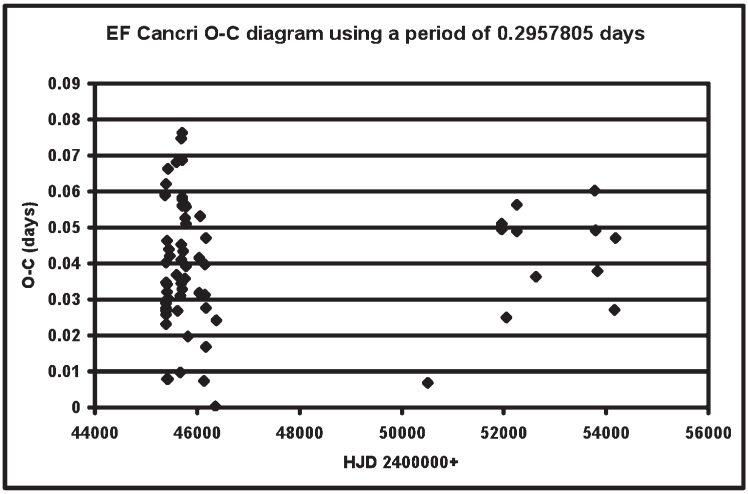

Fig. 1

The modified GEOS O – C diagram for EF Cancri from 1983 to 2008 plotted with an ephemeris of 2446352·804 + 0·2957805 *E* days.

EF Cancri

The star EF Cancri was classed as a W UMa variable following observations by Kippenhahn[3] in 1955 and by Locher[4] in 1983. It is still described as such in the *Simbad* database. However, later observations by Pejcha & Sobotka[5] in 2001 showed that the star is probably an RRc variable. They found a best-fit period of 0·2956885 days and this period has been used in the GEOS[6] database to produce the O – C diagram in that database. The GEOS database contains 66 observations of EF Cancri obtained over a time interval of 24 years. Inspection of the GEOS O – C diagram shows that the adopted period is incorrect as there are continuous runs of steadily increasing O – C values, indicating that the adopted period is too short. Changing this period to 0·2957805 days gives the O – C diagram in Fig. 1. These O – C data have been subjected to period analyses using both the phase-dispersion method and the discrete-Fourier-transform method from the PERANSO suite of programs. Both analyses give similar results and the power spectrum in Fig. 2 shows the DFT result for the frequency range 0·01 to 0·2 c/d. All the signals at higher frequencies than this have much lower power.

Table I lists the details of the three highest peaks. The data do not allow a definitive determination as to which, if any, of these three periods is the correct one, although analyses of subsets of the data indicate that the same periods are present at different times. Fig. 3 shows the data folded with the 10·98-day period corresponding to the highest peak. All three periods show a similar-shaped phase diagram and the point of interest is the smooth shape of the variations. Their continuous, sine-like shape is in stark contrast to those for RR Lyrae itself shown in Paper 1 and AR Her in Paper 2. Pre-whitening the data with the 10·98-day period and then reanalysing it shows that the 14·3-day period is still present and the possibility that more than one period is present cannot be ruled

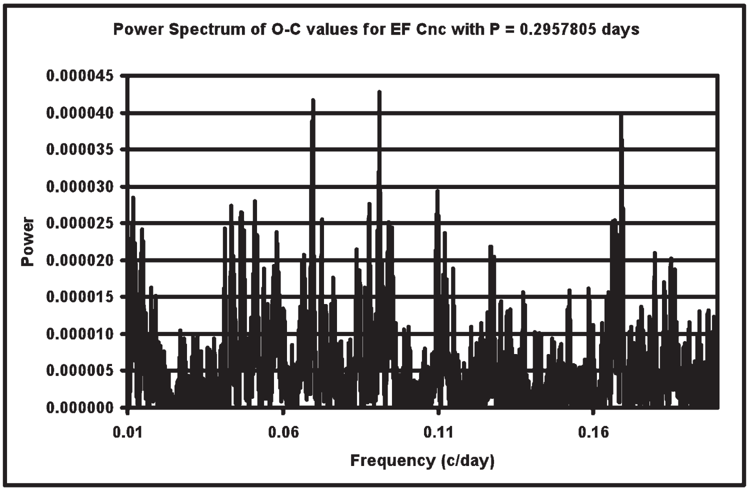

FIG. 2

The power spectrum of the data shown graphically in Fig. 1.

TABLE I

The details of the three most significant peaks in the power spectrum of the EF Cnc O–C values

Frequency (*c*/*d*)	*s.e.*	*Period* (*days*)	*s.e.*	*Amplitude* (*days*)
0·06962	0·00004	14·363	0·008	0·019
0·09107	0·00004	10·980	0·005	0·026
0·16931	0·00004	5·906	0·002	0·013

out. It will require more, better-spaced data to investigate this possibility. The periods and their respective amplitudes would seem to preclude these variations being due to light-travel times in a binary system. The spacing of these data, which have a Nyquist period of 2 days, does not allow the investigation of the 0·5912-day period which was originally determined when the star was thought to be an EW variable.

BD Draconis

The star BD Draconis is listed in the GEOS RR Lyrae database as being an RRab with a period of 0·5890520 days. The GEOS O – C diagram shows almost vertical runs of data indicating that the adopted period is incorrect. Further analysis determined that a change of period to a value of 0·5789645 days is a better fit to the whole 110 years of data. Fig. 4 shows the new O – C diagram determined using that period. It should be understood that the data are sparse enough, and the pulsation period so variable, that it is not possible to determine a unique O – C diagram. Fig. 4 is the most self-consistent diagram we could determine but other solutions are possible.

It is clear that the pulsation period has not remained constant over the approximately 110 years covered by these data. The first nineteen years HJD (2 400 000; hereinafter omitted) +15 373 (1900) to HJD +22 071 (1919) and last

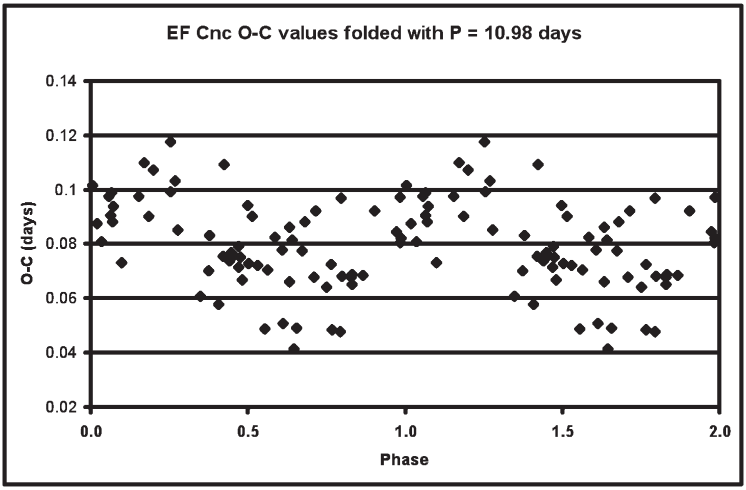

FIG. 3
The EF Cnc O – C values folded with a period of 10·98 days.

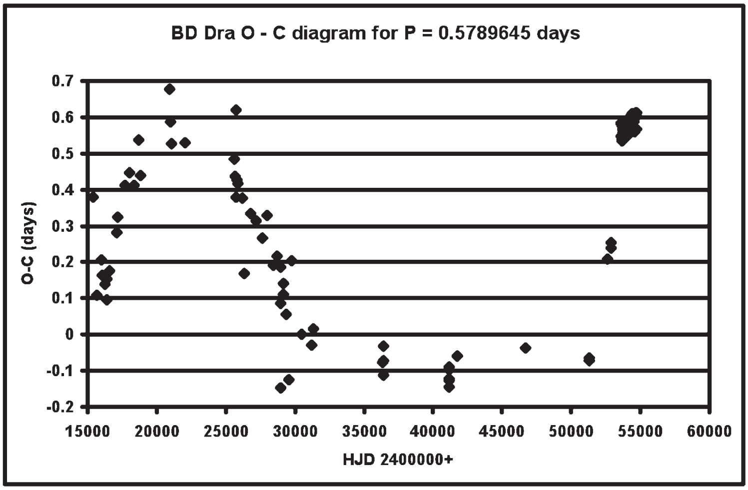

FIG. 4
The O – C values of BD Dra from 1900 to 2008 plotted using an ephemeris of 2430464·514 + 0·5789645 *E* days.

ten years HJD +51 296 (1999) to HJD +54 753 (2008) of data have a period of about 0·58896 days while the data from HJD +25 000 (1928) to HJD +32 000 (1944) are best fitted with a period of about 0·589017 days. Attempts to use the shapes of RR Lyrae O – C diagrams as evidence of evolution of the stars across the H–R diagram have to be able to explain this type of variation.

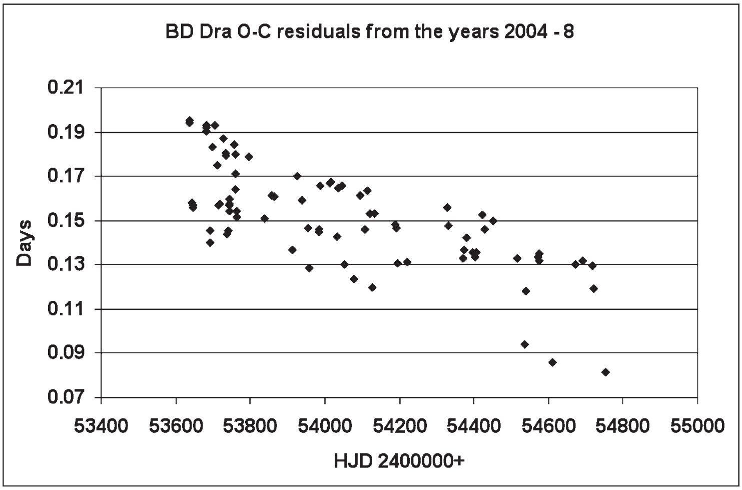

FIG. 5
An enlarged view of the O – C values for BD Dra from 2004 to 2008 inclusive.

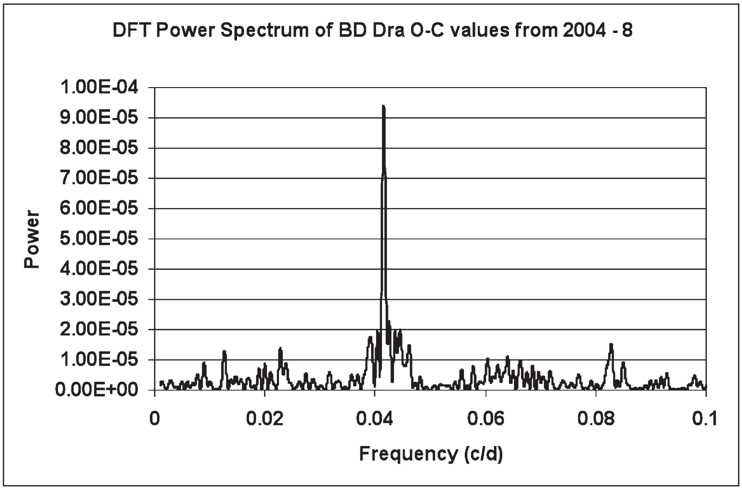

FIG. 6
The power spectrum for the data in Fig. 5 after it has been detrended.

The short vertical runs of data along the horizontal part of the diagram suggest that another period is present.

Several attempts have been made to use subsets of the data, detrend them, and then search for secondary periods. The last 1200 days of data do show a clearly periodic signal. This subset of the data is shown with an expanded scale in Fig. 5 and the power spectrum obtained by the discrete-Fourier-transform method is

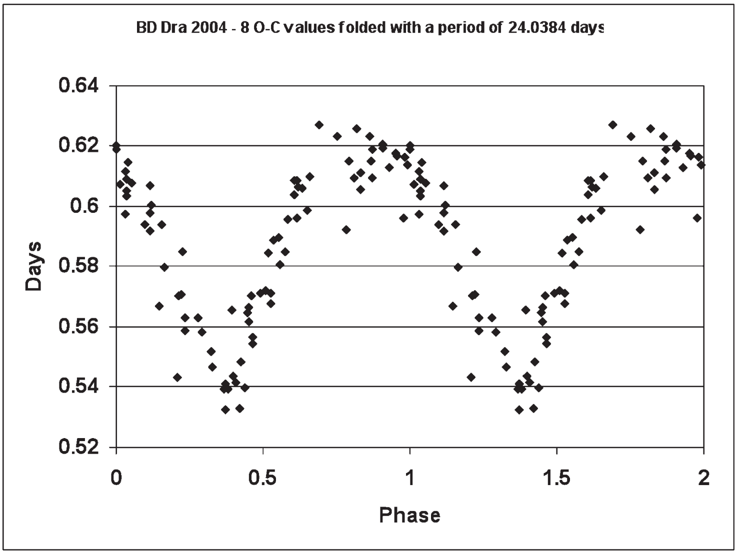

FIG. 7

The O – C values for the years 2004 to 2008 inclusive folded with a period of 24·0384 days.

shown in Fig. 6. The significant peak is at 0·04156 ± 0·00021 c/d (24·0384 ± 0·1216 days). This subset of the data folded with this period is shown in Fig. 7; two complete cycles are shown. A check has also been made to discover whether the variations could have double that period so that there would be two maxima and minima per complete cycle. The resultant phase diagram does not look realistic and it would need radial-velocity data to discover whether there is any possibility that a 48-day period is correct. Lacking any such evidence then it seems that the 24-day phase diagram in Fig. 7 is likely to be the correct one.

The clarity of the signal in both Figs. 5 and 6 is such that the earlier data has been searched for the same signal, despite it not previously showing clear periodicity. The earliest nineteen years of data have a significant signal at 23·370 ± 0·023 days and those data folded with that period have the same shaped curve as in Fig. 7. There is no significant period in the data from 1928 to 1944. The horizontal part of the O – C plot, which runs from 1958 to 1999, has possible periods at both 22·85 days and 25·26 days, but these data are so sparse that no result from these data alone can be regarded as real. This raises a question as to what has caused the differences in the results at different epochs. While it is clear that the most recent data are both more numerous and more continuous than the earlier data, it is not evident that the earliest data has any intrinsic faults. Indeed, the fact that it is possible, with hindsight, to discover the 24-day signal in the earliest 19 years of data suggests that the data are capable of showing this signal. Note that the earlier period is 23·370 ± 0·023 days and the latest period is 24·093 ± 0·116 days. If the formal standard errors are a realistic estimate of the true errors then this period has increased over 100 years. Between 1928 and 1999 this 24-day period was either absent or not detectable.

Summary and discussion

The motivation behind the present analysis was to make minor corrections to the pulsation periods of the RR Lyr stars EF Cnc and BD Dra and then to investigate the revised O – C diagrams to discover whether there was any periodicity in the O – C values with a view to the possible discovery of Blazhko-effect periods. The runs of data plotted in Fig. 1 for EF Cnc indicate that the variations in the O – C values are not just scatter. The 11-day period could be evidence for a Blazhko cycle but this period is not clearly the definitive one and the significance of the 14-day and 5·9-day periods needs to be checked from new and better data. The existing data are neither numerous enough nor continuous enough to allow an investigation to determine whether these periods are present all the time and, if so, whether these variations are locked in phase. For BD Dra a period of 24 days is certainly present in the more recent data. However, even knowing of its presence, it is difficult, or impossible, to detect it in the earlier data and it would not have been discovered from those data alone. The evidence at the moment is that the 24-day period has lengthened by about 3% over the last 100 years.

Noting that the O – C values represent the advance and retardation of the maximum in the pulsation light-curve from a monotonic pulsation period, then the shapes of the phase diagrams indicate the way in which the maxima advance and retard. The smooth, sine-like shape of the curve for EF Cnc can be contrasted with the shape of the curve for BD Dra, which has rounded maxima and sharp minima. Both curves are markedly different from those which were found in Paper 1 for RR Lyr itself and in Paper 2 for AR Her. In both stars, when the curve was 'clean', a linear decline taking about 90% of the Blazhko period for RR Lyr and 70% of the Blazhko period for AR Her was followed by a rapid recovery to the original O – C value. If these secondary periods are evidence of a Blazhko effect with periods of near to 11 and 24 days, then any model for the origin of the Blazhko effect should be able to explain the shapes of these curves and their respective differences from the curves for RR Lyr and AR Her. The ratios of the O – C amplitudes in the secondary periods to the pulsation period for both stars are 0·025/0·5789645 = 4% for EF Cnc and 0·04/0·2957805 = 14% for BD Dra. The value for RR Lyr itself was 14% and for AR Her 13%. The shape of the Blazhko period O – C phase diagram in RR Lyr was only 'clean' for three years out of the 109 years covered by the data. In Paper 1 it was suggested that if the 'clean' curve were the correct one for the Blazhko variations, then for most of the time there was another source of variation present. It is possible that what is seen in this paper are such variations and are not Blazhko variations, but their origins remain to be explained.

It seems worthwhile to address the question as to whether the periodic O – C variations discovered in both EF Cnc and BD Dra could be due to light-travel times in binary star systems. RR Lyrae-type stars are thought to have evolved off the main sequence and perhaps be two magnitudes brighter than similar-mass stars which have yet to evolve. There is no suggestion from spectroscopic work that either star is double-lined and therefore any companion star, which is not a sub-luminous dwarf, is unlikely to have a mass which is much greater than that of the RR Lyrae variable itself. If the value of about 0·7 $M_{\odot}$ is adopted for the variables then it is unlikely that the total mass of any putative binary system will exceed 2 $M_{\odot}$. With periods in the 10-to-24-day range and amplitudes of 0·025 to 0·08 days, it seems impossible that the observed phase diagrams can be the result of orbital motion.

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SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 213: HD 179332, HD 181386, AND THEIR VISUAL COMPANIONS

By R. F. Griffin
Cambridge Observatories

HD 179332 is an 8^{m} double-lined object that consists of a pair of late-type subgiants in an eccentric orbit having a period of 3½ years. A conspicuous optical companion about 47″ distant proves also to be a spectroscopic binary, with an eccentric 2-year orbit. HD 181386, which has been classified as G5 II, is in a low-eccentricity orbit with a period of about 3 years. It is the primary of a recognized double star having a separation of about 12″; the pair has shown little or no orbital motion in nearly 200 years, but evidently has common, though small, proper motion. The secondary, too, is a binary, in a circular orbit with a period of 90 days. The similarity of the γ-velocities makes it practically certain that the visual pair does constitute a physical binary, and the system is thus quadruple.

Introduction

The two pairs of stars discussed here are in almost the same right ascension but are far apart in declination — HD 179332 is above 60°, in a barren region of Draco about 7° south of δ Draconis, whereas HD 181386 is only 4° north of the equator, a little less than 2° north-preceding δ Aquilae. HD 179332 came to the writer's attention by being noted as a double-lined binary by Rastorguev & Glushkova[1], while HD 181386 was found to be a spectroscopic binary by de Medeiros & Mayor[2]. Both stars were placed on the observing programme in the summer of 2002; both had obvious visual companions which the observer's natural curiosity prompted him to measure, and both the companions turned out to be themselves spectroscopic binaries, whose orbits are given here along with those of their primaries. All of the new observations in this paper have been made with the Cambridge *Coravel*.

HD 179332 and its companion

Of the four stars, only HD 179332 was observed by *Hipparcos*, which found for it a parallax that equates to a distance modulus of $6^m \cdot 03 \pm 0^m \cdot 22$. There does not seem to be any ground-based *UBV* photometry of the star, but *Tycho* provided its V and $(B - V)$ as $8^m \cdot 24$ and $0^m \cdot 88$, respectively. It is seen, therefore, that the system has an integrated M_V slightly fainter than $+2^m$, so both stars must be subgiants — surely a quite unusual case, but one that had already been made for the star by its classification by Woolley *et al.*[3] as G9 IV. *Tycho* also gave photometry for the visual secondary star, which is about 47″ distant in position angle about 318°, as $V = 9^m \cdot 16$, $(B - V) = 1^m \cdot 06$. Taken in conjunction with its very small proper motion, the colour suggests a type of something like gK0 for the object.

There are 42 radial-velocity observations of the double-lined visual primary, of which four were taken at phases when the two spectra were too closely blended to be resolved, leaving 38 from which to derive the orbit. Fig. 1 shows the very first observation, which was fortuitously made right at the node of the orbit when the spectra were at their maximum separation. In the solution of the orbit, it has proved necessary to down-weight the velocities of the secondary by a factor of ten to equalize the weighted variances. The measurements are set out in Table I; the orbital elements are as follows:

P	=	$1293 \cdot 4 \pm 1 \cdot 2$ days	$(T)_1$	=	MJD $53747 \cdot 3 \pm 1 \cdot 1$
γ	=	$-1 \cdot 29 \pm 0 \cdot 04$ km s^{-1}	$a_1 \sin i$	=	$229 \cdot 4 \pm 1 \cdot 2$ Gm
K_1	=	$14 \cdot 70 \pm 0 \cdot 07$ km s^{-1}	$a_2 \sin i$	=	$236 \cdot 6 \pm 2 \cdot 7$ Gm
K_2	=	$15 \cdot 16 \pm 0 \cdot 17$ km s^{-1}	$f(m_1)$	=	$0 \cdot 288 \pm 0 \cdot 004\ M_\odot$
q	=	$1 \cdot 032 \pm 0 \cdot 012$ ($= m_1/m_2$)	$f(m_2)$	=	$0 \cdot 316 \pm 0 \cdot 011\ M_\odot$
e	=	$0 \cdot 4798 \pm 0 \cdot 0031$	$m_1 \sin^3 i$	=	$1 \cdot 23 \pm 0 \cdot 03\ M_\odot$
ω	=	$154 \cdot 1 \pm 0 \cdot 5$ degrees	$m_2 \sin^3 i$	=	$1 \cdot 189 \pm 0 \cdot 019\ M_\odot$

R.m.s. residual (unit weight) = $0 \cdot 22$ km s^{-1}

The *RO Annals*[3] give three radial velocities measured from 66-Å mm^{-1} plates taken at Kottamia in 1966; they are listed with standard errors of about 5 km s^{-1} and did not allow the double-lined nature of the star to be discovered — they were in any case all obtained near a time when it was single-lined. They are, however, listed in Table I, and plotted in Fig. 2 which illustrates the orbit, as are the twin velocities measured on a single occasion by Rastorguev & Glushkova[1],

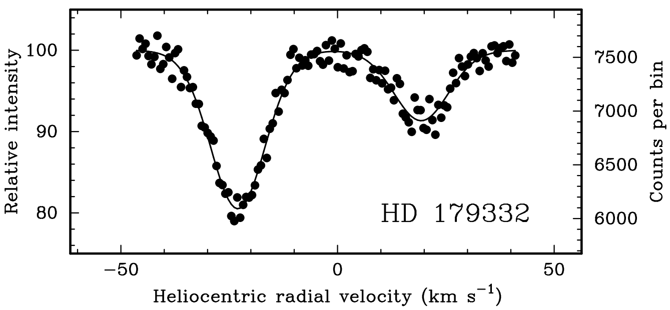

FIG. 1

The first Cambridge radial-velocity trace of HD 179332, obtained on 2002 July 26.

TABLE I

Radial-velocity observations of HD 179332

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

Date (UT)	MJD	Velocity Prim. km s⁻¹	Velocity Sec. km s⁻¹	Phase	(O–C) Prim. km s⁻¹	(O–C) Sec. km s⁻¹
1966 June 18·04*	39294·04	−4·2		$\overline{11}$·825	—	—
Oct. 2·69*	400·69	+2·6		·908	—	—
12·74*	410·74	−3·6		·916	—	—
1988 Aug. 15·02†	47388·02	−17·3	+15·7	$\overline{4}$·083	−0·7	+1·2
2002 July 26·96	52481·96	−22·1	+20·2	0·022	+0·2	−0·2
Aug. 13·02	499·02	−22·1	+19·8	·035	−0·1	−0·2
Sept. 2·95	519·95	−20·9	+18·3	·051	−0·3	−0·3
Oct. 3·86	550·86	−17·4	+15·7	·075	+0·3	+0·1
Nov. 4·84	582·84	−14·4	+12·8	·100	+0·1	+0·5
Dec. 9·77	617·77	−11·3	+9·8	·127	0·0	+0·7
2003 Feb. 18·25	52688·25	−6·1	+3·6	0·181	+0·2	−0·3
Mar. 19·17	717·17	−4·9	+1·2	·204	−0·2	−1·0
Apr. 19·12	748·12	−2·3		·228	—	—
June 21·06	811·06	−1·0		·276	—	—
July 13·97	833·97	−0·6		·294	—	—
Aug. 8·99	859·99	−0·4		·314	—	—
Sept. 13·95	895·95	+1·8	−3·4	·342	0·0	+1·1
Oct. 18·79	930·79	+2·9	−4·0	·369	+0·2	+1·4
Nov. 27·84	970·84	+3·2	−5·1	·400	−0·3	+1·1
Dec. 28·76	53001·76	+4·0	−6·4	·424	−0·1	+0·4
2004 Feb. 9·25	53044·25	+4·9	−7·6	0·456	+0·1	0·0
Mar. 31·18	095·18	+5·9	−8·9	·496	+0·4	−0·6
May 19·11	144·11	+6·1	−8·3	·534	0·0	+0·6
June 17·08	173·08	+6·4	−10·1	·556	0·0	−0·9
Aug. 11·03	228·03	+6·7	−10·4	·599	−0·1	−0·8
Sept. 1·96	249·96	+6·7	−10·1	·616	−0·2	−0·4
Oct. 5·88	283·88	+6·9	−9·8	·642	−0·1	+0·1
Nov. 12·83	321·83	+6·9	−10·0	·671	−0·2	−0·1
Dec. 6·82	345·82	+7·2	−9·7	·690	+0·2	+0·2
2005 Jan. 8·74	53378·74	+6·5	−10·1	0·715	−0·4	−0·4
Mar. 25·19	454·19	+5·8	−8·3	·773	−0·3	+0·6
Apr. 22·15	482·15	+5·8	−7·0	·795	+0·3	+1·3
May 15·10	505·10	+5·2	−8·4	·813	+0·3	−0·7
July 17·03	568·03	+2·3	−3·4	·861	+0·1	+1·5
Oct. 4·82	647·82	−4·8	+2·1	·923	+0·3	−0·6
25·88	668·88	−8·5	+5·6	·939	−0·3	−0·2
Nov. 13·89	687·89	−11·4	+10·3	·954	0·0	+1·2
29·83	703·83	−14·5	+11·9	·966	−0·3	−0·2
Dec. 17·75	721·75	−17·1	+15·6	·980	+0·3	+0·3
2006 Apr. 5·15	53830·15	−19·3	+16·2	1·064	−0·2	−0·9
May 6·13	861·13	−15·9	+14·9	·088	+0·1	+1·0
June 4·07	890·07	−13·3	+11·9	·110	−0·1	+0·9
July 12·05	928·05	−9·9	+8·3	·140	+0·1	+0·6
Aug. 8·02	955·02	−8·1	+6·2	·161	−0·1	+0·5
2008 Aug. 30·94	54708·94	+6·5	−9·6	1·744	−0·1	−0·2
2009 July 20·06	55032·06	−20·0	+17·3	1·993	−0·1	−0·6

* Observation by Woolley *et al.*[3]; weight 0.
† Observation by Rastorguev & Glushkova[1]; weight 0.

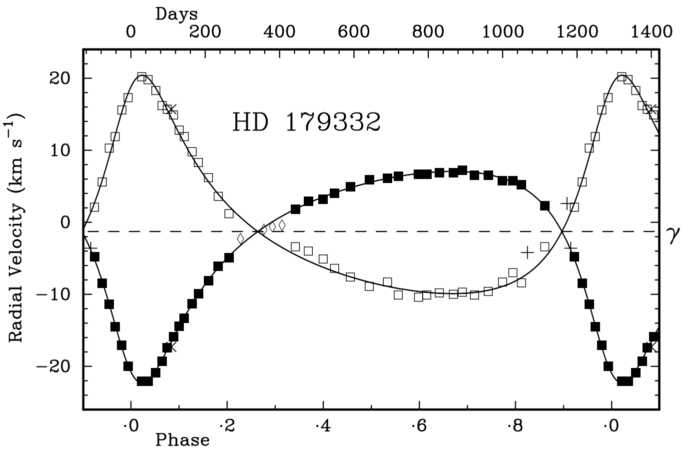

FIG. 2

The observed radial velocities of HD 179332 plotted as a function of phase, with the velocity curves corresponding to the adopted orbital elements drawn through them. The measurements made with the Cambridge *Coravel*, upon which the orbit is based, are represented by squares, filled for the primary star and open for the secondary. Other symbols denote observations not utilized in the orbit, as follows. The four open diamonds near phase ·3 refer to *Coravel* observations made when the components had such similar velocities that the blend could not be reliably disentangled and was reduced as if the system were single-lined. The three plusses near phase ·9 represent Kottamia[3] single-lined measurements; the two crosses near phase ·1 represent the one double-lined observation by Rastorguev & Glushkova[1], which agrees within its own uncertainties with the Cambridge orbit.

although none of those data was included in the solution of the orbit. The residuals of the measurements by the latter authors are of the same order as the uncertainties listed for the observations concerned, so there is not much incentive to try to refine the orbit by appeal to them; it may be mentioned, however, that if they were included in the solution with reasonable weighting, the only appreciable effect on the orbital elements would be a reduction of the period by nearly a day.

In both the publications[3,1] with the previous observations, the times are given in tables headed 'JD' and would, if taken literally, refer to dates before 4000 BC; it is supposed here that the authors neglected to mention that they subtracted 2 400 000 from each of them, but they evidently did not complete the job and subtract also the odd half-day which would have turned the dates into MJDs and brought the times into a normal relationship with UT. There are, however, mixed in the same table in the *RO Annals*[3], other stellar-observation dates which, on the same hypothesis as we have been obliged to adopt in relation to HD 179332, correspond to daylight times, even noontide, at the observing site.

The minimum masses given for HD 179332 by the orbit are near 1·2 $M_{\odot}$, but since the stars are evolved objects we cannot assign true masses to them with any confidence in order to estimate the orbital inclination. That will have to await direct angular resolution. Their separation, projected on the line of sight, $(a_1 + a_2) \sin i$, is some 3 AU, which at the distance of 160 pc that corresponds to the parallax would subtend an angle of nearly 0″·02 — though that figure is only indicative because the projection of the separation vector on the sky is on quite a different plane to that of the orbit.

TABLE II

Cambridge radial-velocity observations of HD 179332 B

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2002 July 26·96	52481·96	−34·1	0·129	+0·2
Aug. 13·03	499·03	−34·6	·154	0·0
Sept. 2·95	519·95	−35·2	·184	−0·2
Nov. 4·85	582·85	−36·7	·276	−0·5
Dec. 9·78	617·78	−36·4	·326	+0·4
2003 Feb. 18·25	52688·25	−37·5	0·429	+0·4
Mar. 19·17	717·17	−38·7	·471	−0·4
Apr. 19·13	748·13	−38·5	·516	+0·2
May 15·11	774·11	−39·4	·553	−0·3
June 21·07	811·07	−39·7	·607	−0·1
July 13·98	833·98	−39·6	·640	+0·3
Aug. 8·99	859·99	−40·3	·678	0·0
Sept. 13·94	895·94	−40·6	·730	+0·1
Oct. 18·79	930·79	−41·1	·781	+0·1
Nov. 27·84	970·84	−41·8	·839	−0·2
Dec. 28·75	53001·75	−41·7	·884	0·0
2004 Feb. 9·26	53044·26	−41·2	0·946	−0·6
Mar. 31·18	095·18	−35·5	1·020	+0·3
Apr. 7·16	102·16	−35·2	·030	0·0
20·12	115·12	−34·2	·049	+0·3
May 17·09	142·09	−34·0	·088	0·0
June 17·08	173·08	−34·4	·133	0·0
Aug. 8·04	225·04	−34·8	·209	+0·5
Sept. 1·95	249·95	−35·7	·245	+0·1
Oct. 5·88	283·88	−36·2	·294	+0·2
Nov. 12·82	321·82	−36·9	·349	+0·1
Dec. 11·71	350·71	−37·5	·391	0·0
2005 Jan. 8·73	53378·73	−37·9	1·432	0·0
May 8·12	498·12	−39·7	·605	−0·1
June 1·09	522·09	−40·1	·640	−0·2
July 17·02	568·02	−40·1	·707	+0·4
Dec. 8·74	712·74	−41·8	·917	−0·4
2006 Apr. 4·17	53829·17	−34·4	2·086	−0·4
2007 July 19·99	54300·99	−40·8	2·771	+0·3
Aug. 30·03	342·03	−41·3	·831	+0·3
Oct. 13·89	386·89	−41·0	·896	+0·7
19·87	392·87	−41·8	·905	−0·2
Dec. 5·80	439·80	−38·9	·973	+0·3
12·78	446·78	−38·4	·983	+0·1
2008 May 22·06	54608·06	−35·1	3·217	+0·4
Aug. 30·94	708·94	−37·3	·364	−0·1
Oct. 31·82	770·82	−38·7	·454	−0·6
Nov. 22·73	792·73	−38·7	·486	−0·3
Dec. 26·71	826·71	−39·2	·535	−0·3
2009 Jan. 20·73	54851·73	−39·4	3·571	−0·1
July 1·07	55013·07	−41·5	·806	−0·1
Sept. 25·90	099·90	−41·3	·932	−0·2
Oct. 8·86	112·86	−40·3	·951	+0·1
19·93	123·93	−39·6	·967	0·0
Nov. 3·81	138·81	−38·1	·988	0·0
23·71	158·71	−36·1	4·017	−0·1
Dec. 6·76	171·76	−34·8	·036	+0·1
17·75	182·75	−35·1	·052	−0·7
28·73	193·73	−34·2	·068	−0·1

The visual companion to HD 179332 has its own official designations, including that of BD +60° 1892, but for the purposes of this paper we will call it informally HD 179332 B, and identify the companion to HD 181386 analogously. The 54 radial-velocity measurements of HD 179332 B are given in Table II and lead readily to the orbit shown in Fig. 3 and having the following elements:

P	=	$688{\cdot}4 \pm 0{\cdot}9$ days	$(T)_2$	=	MJD $53769{\cdot}9 \pm 2{\cdot}9$
γ	=	$-38{\cdot}21 \pm 0{\cdot}05$ km s^{-1}	$a_1 \sin i$	=	$32{\cdot}0 \pm 0{\cdot}6$ Gm
K	=	$3{\cdot}85 \pm 0{\cdot}06$ km s^{-1}	$f(m)$	=	$0{\cdot}00277 \pm 0{\cdot}00015\ M_\odot$
e	=	$0{\cdot}476 \pm 0{\cdot}013$			
ω	=	$280{\cdot}3 \pm 2{\cdot}3$ degrees	R.m.s. residual	=	$0{\cdot}29$ km s^{-1}

The only conclusion that we can draw — and even this is a tentative one in the absence of any other hard information about the stars — relies on an estimate that its mass is something like 2 $M_\odot$ since we have supposed it to be a giant. In that case the minimum secondary mass would be about 0·55 $M_\odot$, corresponding to that of a late-K main-sequence star; if the secondary were a white dwarf it would not be likely to have left the orbit so eccentric after its giant-branch evolution.

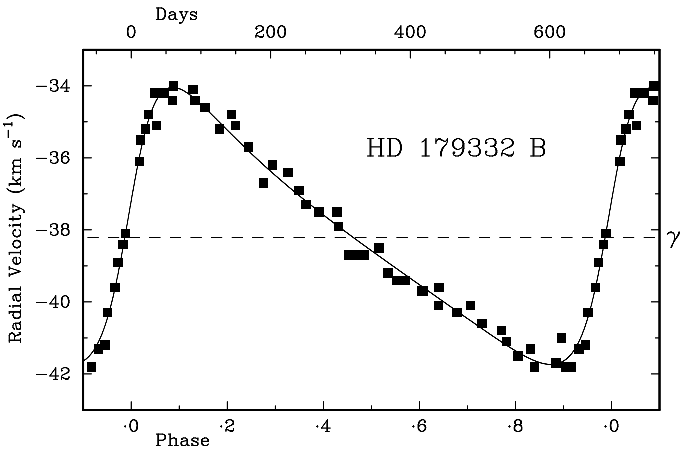

FIG. 3

The observed radial velocities of HD 179332 B plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them.

HD 181386 and its companion

Unlike HD 179332, HD 181386 is the primary of an 'old-established' visual double star, first listed by Struve[4] as Σ 2498 and measured[5] by him in 1825; he gave a *Δm* of $0^{m}{\cdot}6$, a separation of 12″·16, and a position angle of 66°·2. The system is now usually known as ADS[6] 12322. It was not observed by *Hipparcos*, but *Tycho* has given the V magnitudes of the pair as $8^{m}{\cdot}07$ and $8^{m}{\cdot}89$ and their $(B-V)$ colour indices as $1^{m}{\cdot}07$ and $0^{m}{\cdot}96$. Fernie[7] measured the primary only, and found $V = 8^{m}{\cdot}22$, $(B-V) = 1^{m}{\cdot}08$, $(U-B) = 0^{m}{\cdot}77$; the discrepancy with the *Tycho* V magnitude is great enough to suggest that (much of) the change

TABLE III

Radial-velocity observations of HD 181386

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

Date (UT)	MJD	Velocity km s⁻¹	Phase	(O – C) km s⁻¹
1942 June 28·38*	30538·38	+16·8	0·822	+2·2
1943 Aug. 12·23*	30948·23	4·0	1·183	−1·4
1944 May 3·44*	31213·44	2·7	1·416	−2·9
1946 Sept. 17·17*	32080·17	9·8	2·178	+4·3
1986 May 31·10†	46581·10	14·3	14·930	0·0
1987 June 14·07†	46960·07	4·5	15·263	0·0
1997 Aug. 30·93†	50690·93	7·9	18·544	−0·3
Sept. 18·85†	709·85	8·7	·561	+0·1
2002 June 2·06	52427·06	9·1	20·071	+0·1
July 14·02	469·02	7·8	·107	+0·2
Sept. 1·89	518·89	6·2	·151	+0·1
Oct. 4·89	551·89	4·5	·180	−0·9
Nov. 12·75	590·75	4·3	·215	−0·5
Dec. 4·71	612·71	4·6	·234	0·0
2003 May 18·08	52777·08	4·8	20·378	−0·3
June 19·06	809·06	6·0	·407	+0·5
July 13·02	833·02	6·4	·428	+0·6
14·03	834·03	5·9	·428	+0·1
Aug. 8·98	859·98	6·5	·451	+0·3
Sept. 13·92	895·92	6·9	·483	+0·1
Oct. 14·84	926·84	7·4	·510	0·0
Nov. 26·71	969·71	8·3	·548	0·0
Dec. 7·71	980·71	8·4	·557	−0·1
2004 Apr. 23·12	53118·12	11·4	20·678	−0·2
May 31·07	156·07	12·8	·712	+0·4
June 17·07	173·07	13·1	·727	+0·3
Aug. 11·02	228·02	13·7	·775	−0·1
Sept. 5·95	253·95	14·5	·798	+0·3
Oct. 25·80	303·80	14·9	·842	+0·1
Nov. 26·72	335·72	14·7	·870	−0·2
2005 Apr. 19·14	53479·14	12·5	20·996	+0·2
May 8·10	498·10	10·9	21·012	−0·7
June 9·04	530·04	10·7	·041	+0·3
23·04	544·04	10·1	·053	+0·3
July 22·01	573·01	8·8	·078	+0·1
Aug. 2·93	584·93	8·5	·089	+0·2
Sept. 7·89	620·89	7·4	·120	+0·3
20·90	633·90	6·8	·132	+0·1
Oct. 27·77	670·77	5·8	·164	0·0
Nov. 29·71	703·71	5·6	·193	+0·4
2006 Apr. 4·18	53829·18	4·4	21·304	−0·1
26·14	851·14	4·4	·323	−0·2
May 30·11	885·11	4·9	·353	+0·1
July 12·04	928·04	+5·3	·391	+0·1

TABLE III (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2007 Apr. 2·18	54192·18	+9·2	21·623	−0·9
May 1·12	221·12	10·1	·648	−0·7
19·11	239·11	11·4	·664	+0·2
June 28·07	279·07	12·6	·699	+0·5
2008 Apr. 24·13	54580·13	13·0	21·964	−0·4
Sept. 18·90	727·90	+7·7	22·094	−0·4

*Observation by Wilson & Joy[10,11]; weight 0.
†Observation by de Medeiros & Mayor[2]; weight 1.

must be real. The angular separation is still as Struve found it, but the position angle may have decreased marginally. The *Tycho 2* proper motions of the stars are only about 0″·8 per century and are identical within their uncertainties of little more than 0″·1 per century. Stephenson[8] classified the primary star as G5 II; Abt[9] gave G2 II for the primary and G2 III for the secondary.

Wilson & Joy[10] published a mean radial velocity of +7·5 km s^{-1} from four Mount Wilson spectrograms of HD 181386, with a 'probable error' of 2·1 km s^{-1} and no suggestion that the velocity was variable; they also gave its type as gG5. Abt[11] later published the times and velocities (which ranged from +1·9 to +16·0 km s^{-1}) of the four observations separately, showing that three of them were only at classification dispersion of 80 Å mm^{-1}. Much later, de Medeiros & Mayor[2] gave the results of just two *Coravel* measurements as a mean value of +8·69 ± 4·88 km s^{-1}; that could be seen as an oblique way of saying that the two individual velocities were +3·81 and +13·57 km s^{-1}. After about three years they lodged with the CDS a table giving the individual details of all the velocities reported only as means in ref. 2; the velocities of HD 181386 were there shown slightly

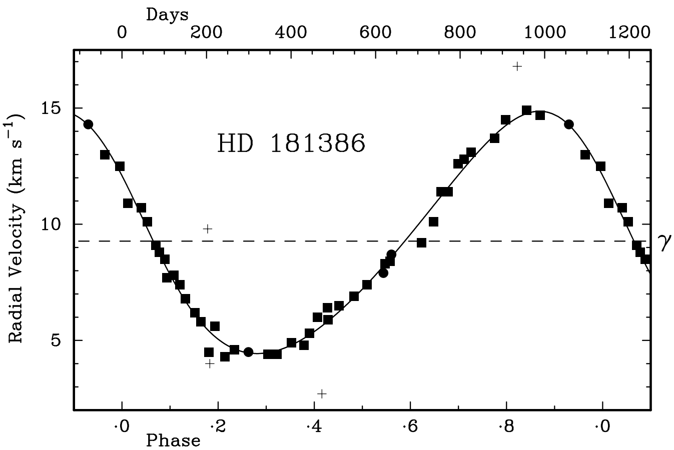

FIG. 4

As Fig. 3, but for HD 181386. The four plusses represent the Mount Wilson observations[10,11], which were not taken into account in the solution of the orbit. The four filled circles plot the velocities measured by de Medeiros & Mayor[2].

TABLE IV

Radial-velocity observations of HD 181386 B

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

Date (UT)	*MJD*	*Velocity* *km s^{-1}*	*Phase*	*(O – C)* *km s^{-1}*
1943 Aug. 12·26*	30948·26	+20·2	$\overline{238}$·975	−2·6
1944 May 3·48*	31213·48	+36·6	$\overline{235}$·905	+9·4
1946 Sept. 17·23*	32080·23	−2·2	$\overline{225}$·482	−0·3
1949 July 6·36*	33103·36	+24·6	$\overline{214}$·786	−2·6
2002 June 2·06	52427·06	−6·9	0·290	+0·2
July 14·02	469·02	+25·6	·754	+0·1
15·01	470·01	+25·7	·765	−0·4
21·01	476·01	+28·2	·831	−0·2
26·07	481·07	+27·6	·887	−0·3
Aug. 12·99	498·99	+11·0	1·085	−0·3
17·01	503·01	+5·5	·129	−0·7
27·88	513·88	−4·6	·249	+0·4
Sept. 1·89	518·89	−7·4	·305	+0·2
8·97	525·97	−7·7	·383	0·0
22·86	539·86	+3·7	·536	+0·2
Oct. 12·81	559·81	+25·9	·757	+0·2
23·81	570·81	+28·4	·878	+0·3
Nov. 12·76	590·76	+9·9	2·099	+0·2
Dec. 4·71	612·71	−8·6	·341	−0·4
2003 May 18·09	52777·09	+3·1	4·158	0·0
June 19·06	809·06	+1·2	·511	+0·4
28·06	818·06	+11·8	·610	0·0
July 14·03	834·03	+26·9	·787	−0·3
15·00	835·00	+27·6	·797	0·0
27·94	847·94	+25·6	·940	+0·3
Aug. 2·96	853·96	+20·0	5·007	+0·2
3·99	854·99	+19·1	·018	+0·4
6·99	857·99	+14·8	·051	−0·3
8·97	859·97	+12·4	·073	−0·2
20·01	871·01	−0·5	·195	+0·2
20·90	871·90	−1·6	·205	0·0
Sept. 10·96	892·96	−5·8	·438	−0·6
13·91	895·91	−3·1	·470	−0·3
14·89	896·89	−1·9	·481	0·0
22·89	904·89	+7·1	·570	0·0
23·82	905·82	+8·3	·580	0·0
24·84	906·84	+9·4	·591	−0·2
28·89	910·89	+14·5	·636	−0·2
Oct. 3·82	915·82	+20·2	·690	−0·2
18·80	930·80	+28·6	·856	+0·2
27·77	939·77	+24·3	·955	0·0
29·81	941·81	+22·2	·978	−0·3
Nov. 3·76	946·76	+17·5	6·032	+0·3
Dec. 7·71	980·71	−6·6	·407	+0·2
2004 Apr. 23·12	53118·12	+26·4	7·926	+0·2
June 17·07	173·07	+3·5	8·533	+0·4
28·03	184·03	+16·6	·654	0·0
July 3·03	189·03	+22·5	·709	+0·4
5·08	191·08	+23·6	·732	−0·3
Sept. 7·84	255·84	−4·9	9·447	−0·3

TABLE IV (*concluded*)

Date (UT)	*MJD*	*Velocity km s⁻¹*	*Phase*	*(O – C) km s⁻¹*
2005 May 8·11	53498·11	+6·6	12·124	−0·2
July 18·03	569·03	+27·0	·908	−0·1
Aug. 15·97	597·97	−3·2	13·227	+0·2
2007 July 19·98	54300·98	+21·2	20·995	+0·2
2008 Oct. 31·77	54770·77	+0·4	26·185	+0·1
Nov. 7·77	777·77	−6·0	·263	−0·2
2009 Sept. 12·93	55086·93	+19·5	29·679	+0·3
Oct. 8·84	112·84	+23·6	·965	0·0

*Observation by Wilson & Joy[10,11]; weight 0.

changed, and two more recent ones had been added to them. It was at that point and from that table that the star was selected for observation at Cambridge, where another 42 measurements have been made of its velocity; they are listed in Table III, which also has the Mount Wilson[10] and OHP[2] observations at its head. The latter (only) have been utilized with the Cambridge measures in the solution of the orbit, which is shown in Table V below (together with that of the secondary star) and is illustrated in Fig. 4. The Cambridge measures alone yield a period of 1139 ± 5 days, which is refined to the value shown in Table V when the OHP velocities are included, with equal weight. The r.m.s. deviations of the four Mount Wilson velocities from the computed orbit is 2·9 km s^{-1} — quite good in relation to their dispersion — whereas the corresponding quantity for their deviations from their own mean is 6·3 km s^{-1}.

The Mount Wilson authors[10] also made four observations of the secondary star (three of them on the same nights as the primary); they gave the spectral type as gG8, and the velocity range was large enough, −3 to +36 km s^{-1}, that they identified the star as a spectroscopic binary and gave the values individually

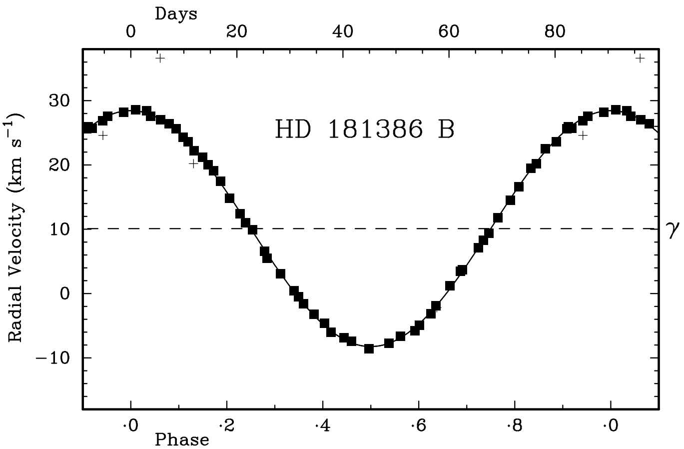

FIG. 5

As Fig. 4, but for HD 181386 B. (One of the four plusses is almost hidden, at phase ·64.)

in an auxiliary table. They still did not give the dates, however, but those too are given in Abt's publication[11] and have been copied to the head of Table IV, which also gives the 54 measurements (coincidentally the same number as for HD 179332 B) made with the Cambridge *Coravel*. The orbital elements derived from the Cambridge observations have been added to Table V, and the orbit itself is shown in Fig. 5. There is certainly no case for considering the orbit as other than circular: when e and ω are allowed as free variables, the sum of the squares of the 54 residuals from the computed orbit decreases from 4·06 only to 4·02 (km s^{-1})^2. The r.m.s. spread of the four Mount Wilson velocities from their own mean is about 14 km s^{-1}; their r.m.s. residual is reduced to 5 km s^{-1} when cognizance is taken of the orbit. Although those observations increase the overall time base from seven to nearly 70 years, they still do not offer any appreciable improvement in the orbit, even its period: to give them the same weighted variance as the Cambridge velocities means attributing them a weight of a few thousandths only, at which they can add virtually nothing to the Cambridge data set.

TABLE V

Orbital elements of HD 181386 A and B

Element	*HD 181386 A*	*HD 181386 B*
P (days)	1137·2 ± 2·6	90·508 ± 0·006
T (MJD)	53484 ± 19	53020·37 ± 0·04
γ (km s^{-1})	+9·27 ± 0·06	+10·11 ± 0·04
K (km s^{-1})	5·22 ± 0·09	18·35 ± 0·06
e	0·155 ± 0·015	0
ω (degrees)	62 ± 6	—
$a_1 \sin i$ (Gm)	80·6 ± 1·5	22·83 ± 0·07
$f(m)$ ($M_\odot$)	0·0162 ± 0·0009	0·0580 ± 0·0005
R.m.s. residual (km s^{-1})	0·35	0·27

The mass function of the visual primary demands for its spectroscopic companion a minimum mass of nearly half a solar mass if its own mass is taken as 2 $M_\odot$, or nearly three-quarters if its own is as much as 4 $M_\odot$. The visual secondary has to have a companion of at least three-quarters of a solar mass if it is 2 $M_\odot$ itself.

An interesting point about Table V is that it shows the γ-velocities of the two stars as differing by only 0·8 km s^{-1}, surely a close enough coincidence to confirm the pair as a true physical binary even without a careful rehearsal of the expectation for the velocity difference in the implied enormous orbit. We are handicapped in making such a rehearsal by substantial uncertainty as to the distance of the system. If we estimated the apparent distance modulus at 9 magnitudes (distance ~600 pc), that would make the secondary (a G giant) about zero absolute magnitude and the primary (a bright giant) about −1. The system is only 4° from the Galactic plane, so there may be appreciable absorption that would mean that the actual distance modulus is somewhat less than the apparent one. Twelve seconds of arc at 600 pc is 7200 AU, which represents a projected (and therefore minimum) separation. The relative velocity (km s^{-1}) is given by the expression $30\sqrt{\Sigma m/a}$ where Σm and a are the total mass and the separation in Solar System units (30 km s^{-1} is the approximate velocity of the Earth in its orbit round the Sun). The total mass of the two giants and their two unseen companions may be expected to be at least 5 $M_\odot$, so the velocity difference in the visual binary might be at least $30\sqrt{5/7200}$ or about 0·8 km s^{-1} — just the observed difference in the γ-velocities. The quantity we have computed refers to a circular orbit; at periastron in an eccentric orbit the velocity could be higher by a factor of $\sqrt{2}$. The period of a circular orbit is $\sqrt{a^3/m}$, which amounts to the order of a quarter of a million years for the orbit adumbrated here.

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SUNDIALS AND LUNAR ECLIPSES

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We show that it is possible for a shadow-casting instrument to be used in a straightforward way to answer with reasonable accuracy the question, "Will there be a lunar eclipse tonight?", using only information recorded on the face of the instrument over a few years. We also show that the existence of the eclipse year and the dependence of the pattern of lunar eclipses on two interacting periodic variations can also become apparent in a natural way by the use of such an instrument.

Introduction

The two principal sources for our understanding of the early study of positional astronomy are written material and scientific instruments. Naturally the quality and quantity of information from these sources is very weak for the earliest developments in astronomy. For example, although we have a reasonable understanding of Babylonian theoretical astronomy[1–3], as has been noted by Goldstein[4], we have little or no knowledge as to how that theoretical work was originally derived from observational astronomy. For almost all other cultures of that period or earlier the evidence we have is much less strong, with generally no texts available. A further difficulty is that, as de Solla Price has pointed out[5], the evidence available from surviving astronomical instruments can be in direct contradiction to that available from texts.

In these circumstances it is reasonable to ask how much could have been achieved by people who had only very simple technology and who lacked an appropriate theoretical understanding of astronomy. It would be possible to investigate this by constructing instruments ourselves from simple materials, and then making observations with them and noting any patterns or phenomena which became apparent. Although that would not assist us in establishing which observations had actually been made historically, and how they had contributed to the development of theoretical astronomy, it may nevertheless be useful in setting some boundaries as to what could have been done.

Unfortunately, the most accurate of the earliest instruments are likely to have been large constructions of stone and wood, and their use is likely to have involved detailed observations over extended periods of time. That would make actual physical experimentation of that nature both costly and time consuming. The approach which we have adopted here is to simulate an instrument by numerical-computation techniques and by this means to try to analyse what might have been deduced from its use. We have modelled a large shadow-casting instrument of the sort which could have been a natural development from the simplest sundials. We have calculated the shadow paths cast on the instrument by both the Sun and the Moon. We have assumed that the observers could make a permanent record on the face of the instrument of the solar shadow paths, and could superimpose temporary records of the lunar shadow paths on that permanent record. In the second part of the work we have also assumed that the observers have the ability to count days and keep simple records of them. Given those assumptions, our analysis has shown that even a relatively straightforward instrument could be used to answer the question, "Will there be a lunar eclipse tonight?", with reasonable accuracy, without the need for any record-keeping beyond that which is marked on the face of the dial. A greater surprise to us was that the existence of the eclipse year and its relationship to the occurrence of eclipses also becomes apparent in a natural way from a simple record of observations.

Observational accuracy

Because we are using numerical computation to generate the shadow paths, our data will have a far higher accuracy than could be obtained by a naked-eye observer, and it is important to have some understanding of the actual accuracy with which observations could be made. There are some good sources of observational data from large shadow instruments which we can use to estimate realistic accuracies, and it is also fairly straightforward to make one's own naked-eye observations.

Waugh[6] used the position of the image of the Sun projected onto the floor of his front hall through an 8-mm hole to determine noon with an error consistently less than ±10 seconds over a period of many years. This corresponds to determining solar azimuth to within $\pm 0°\cdot042$ over a wide range of solar declinations. Jai Singh's 18th-Century Samrat Yantra at Jaipur, which is a traditional equatorial sundial used to determine the time, has a scale with graduations at 2-second intervals[7,8]. It has a 30-m-long gnomon, which is the straight edge of a masonry structure, and the scale has the geometry of part of a co-axial cylinder with a radius of 15 m. Unlike Waugh's image of the Sun projected into his front hall, the scale on Samrat Yantra is viewed in full sunlight. Nevertheless Bhatnagar & Livingston[8] suggest that the instrument can be used to determine solar time to an accuracy of ± 1 second, which corresponds to a determination of the solar hour angle to within $\pm 0°\cdot004$.

Bhatnagar & Livingston's value of ± 1 second may be overly optimistic as values of ± 2 or ± 3 seconds are more commonly quoted for the accuracy of that instrument.

Simple observations of a low Sun shining through a window onto the far wall of a deep room can be used can be used to support these results. If the wall is, say, 8 m from the window then the shadow of the top or bottom of the window will be a straight line which is diffuse over a distance of 70 mm, from deep shadow to full sunlight. For a low Sun, a consistent determination of the edge of the deep shadow, between 'no Sun' and 'some visible Sun', can easily be made with an accuracy of ± 2 mm and good intra-observer reliability. This represents an angular determination of the solar altitude of ± 0°·014. We will use this value, as it is roughly the geometric mean of Waugh's maximum observed error of 0°·042 and Bhatnagar & Livingston's possibly optimistic value of 0°·004. It is between 5 and 14 per cent of the change in solar altitude from one day to the next during three quarters of the year.

It is easier to record lunar shadows than solar shadows, as one can look directly at the reflected image of the Moon without being dazzled. A flat polished surface, such as may be obtained with a piece of quartz or similar mineral, is perfectly adequate to show a good reflection of the Moon. By holding it against the surface on which the shadow is being cast it is possible to determine with very good accuracy the point at which part of the Moon is just visible.

Sundial structure

The soundest starting point for this type of simulation work is the design of the simplest shadow-casting instruments which would have been built because they served some function for the communities which constructed them. It is our view that those would have been instruments to determine the time of year. Price supports this view, stating that the markings on early sundials show that they were principally used as calendars rather than clocks[5]. This makes sense in the context of rural communities, as calendars are often important for successful farming whereas the utility of clocks is less clear. Shepherds, for example, have to plan their year around the 147-day gestation period of sheep, and have to take decisions in October or November which will determine the time of lambing in March or April.

The most appropriate design for a sundial is dependent on the location in which it is to be used. Latitude is clearly important, in particular whether or not the Sun will approach or cross the zenith. The reliability of bright sunshine is also relevant. If regular sunshine can generally be relied upon then a simple noon mark, with observations made only once a day and only on sunny days, will be perfectly adequate for keeping a track of the time of year. A more complex arrangement will be needed in regions where cloud cover is common and where periods of weeks may elapse without a noon sighting of the Sun. In such locations it would be best if a single observation of the Sun at any time of the day could be used to determine the date with good accuracy. These more sophisticated sundials are likely to lead more easily into the construction of useful astronomical instruments. We have therefore chosen to focus on designs which would be appropriate for, say, northern hill country with relatively low solar altitudes and high incidence of cloud or fog.

A simple instrument for determining the date from the position of the Sun can be made from a vertical pillar, a gnomon, on level ground. On a given day the shadow of the top of the pillar will follow a hyperbolic curve on the ground, curving towards the pillar in summer and away from the pillar in winter, and

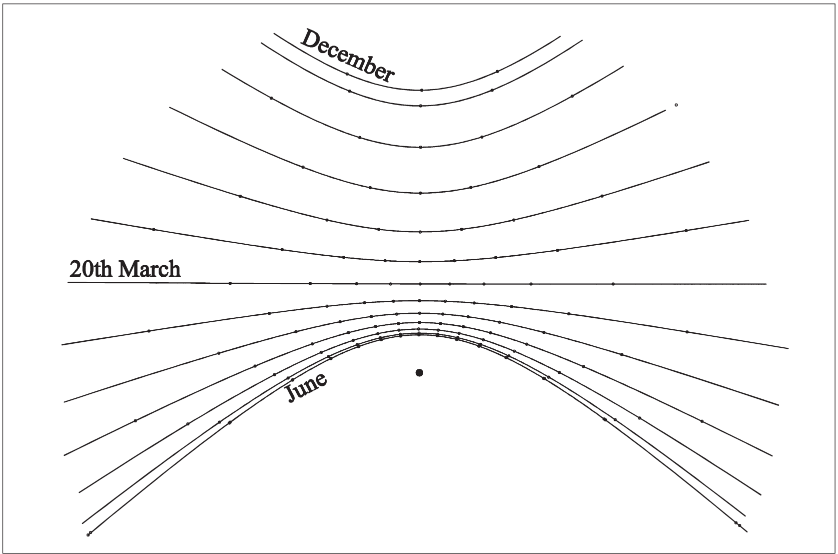

FIG. 1

Shadow paths from a vertical pillar on level ground at fortnightly intervals, midwinter solstice to summer solstice.

following a straight line from east to west at the equinoxes. Fig. 1 shows the shadow paths for a pillar situated at latitude 53°·54 N.

If a line of markers is placed on the ground following the whole path of the shadow on a given day, then in subsequent years a single solar observation at any time of the day will suffice to determine whether the current date is earlier or later in the year than the date on which the markers were set. Creating a selection of such shadow paths, or daily curves, at various times of the year will enable a straightforward calendar to be constructed easily over a few years. Daily curves can be seen on many sundials, usually at monthly intervals.

Because the shadow of the top of a pillar will be diffuse, the accuracy of a vertical gnomon used as a calendar will be low, though probably satisfactory for agricultural purposes. There are several straightforward methods for increasing accuracy, the most common one being to cast a shadow from the edge of a solid object, such as the top of a wall, rather than the top of a pillar. Cylindrical walls, as used in Jai Singh's Ram Yantra and Digamsa Yantra instruments, generally give a suitable geometrical arrangement. The particular geometry we have used here is a broad cylindrical vertical pillar, of radius 1·146 m, surrounded by a coaxial cylindrical wall, with inner radius 4 m. The top of the outer cylindrical wall needs to be smooth and flat, and the pillar needs to have a smooth surface on which the position of the shadow of the wall can be permanently or temporarily marked. A suitable roof could be used to reduce the ambient light at the pillar whilst still allowing the shadow of the top of the wall to fall upon it. The actual dimensions we have used here are arbitrary.

The shadow of the wall on the pillar will have a curved edge, with its highest point on the radius pointing towards the Sun. Marking the positions of the shadow edge where it crosses this radius as both the radius and the shadow edge move throughout the day will give daily curves or date paths on the pillar in much the same way as with the shadow of the top of a vertical gnomon. Although the radius position can be determined by noting the highest point of the shadow, this is unlikely to be accurate enough in practice. This azimuth information needs to be determined with a similar accuracy to that of the solar altitude. It can, however, either be determined by referring to a separate sundial and referencing back to fixed markings on the pillar, or by combining an azimuth arrangement in the single instrument so that the radius position can be observed directly. A number of simple constructions will suffice for this. Provided measurements are consistent from one day to the next the absolute position of the radius does not need to be determined precisely.

The date paths for every other day from midwinter to midsummer, for a calendar of this geometry situated at latitude 53°·54 N, are shown in Fig. 2. The curves appear superficially similar to those found on a shepherd's dial[6], a portable sundial of essentially the same geometry which is used to deduce the time given knowledge of the date, but in that case the horizontal axis is date and the curves are hour paths.

The etching of the solar date paths onto the pillar would be a major undertaking which may take many years to complete, particularly in regions with frequent cloud cover, but the result would be an astronomical instrument of considerable power. Assuming an observational accuracy of ± 0°·014, a single

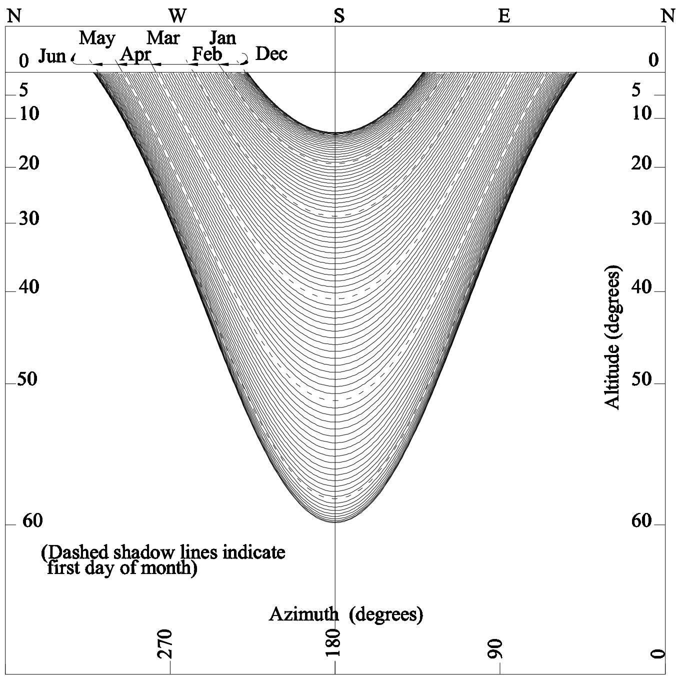

FIG. 2

Date paths made by recording on a central pillar the point where the solar shadow from a concentric cylindrical wall crosses the solar azimuth radius line, for every other day from midwinter solstice to midsummer solstice.

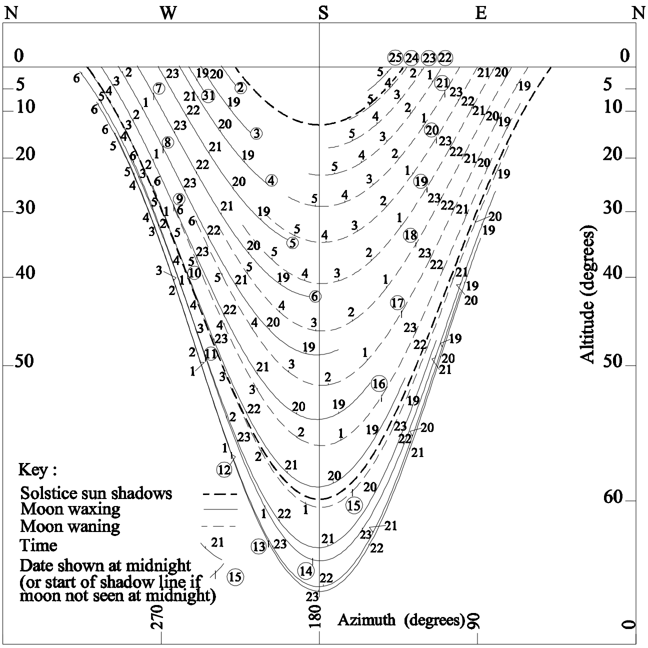

FIG. 3
Lunar shadow lines for each day of 2006 January.

observation of the Sun at any time of the day would easily suffice to determine the date, except for a few days around the solstices.

Lunar observations

If the instrument were also used to record the lunar shadow it would generate some very interesting results. The lunar 'single night' paths for 2006 January are shown in Fig. 3, superimposed on the solar-date paths. The diagram has been constructed for a sundial situated at Bolton, which has latitude 53°·54 N. The lunar shadow moves rapidly across the solar paths, often traversing 20 or more of the solar date paths in one day.

It can be seen that keeping full records of the lunar motion in this form over an extended period of time would be a major undertaking. However, the lunar shadow paths for the previous few days, or perhaps the previous month, could be marked temporarily on the sundial without too much labour. With regard to records which might be preserved over a longer period of time, the solar date path on which the maximum of each observed lunar eclipse fell would be an interesting and straightforward series of observations to maintain. For a total eclipse it may be difficult to determine the lunar position actually during totality, but it would be easy enough to record on which of the solar date paths it occurred. Marking the intersections of these solar date paths with the noon radius line gives a record similar to that given in Fig. 4. This process of using the solar date paths as a method of mapping the current position of the Moon onto the noon radius line is fundamental to the work which follows, and we will

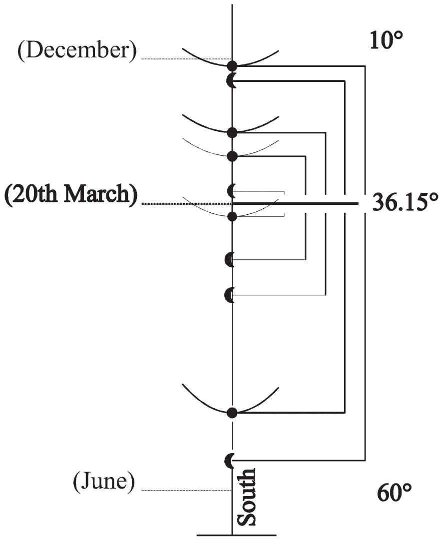

FIG. 4

Lunar and solar altitudes at the time of a lunar eclipse recorded on the noon radius line with corresponding lunar and solar positions linked.

refer to the intersection with the noon radius of the solar date path on which the Moon currently lies as the 'noon equivalent' position of the Moon. Any other vertical reference line could have been used, and we have chosen the noon radius line, the meridian, simply for convenience.

A selection of eclipses has been used from those which were potentially visible on dates between 1998 and 2008 at Bolton. The noon position of the Sun at that time, interpolated as midway between the noon positions on the days either side, has been added and each pair of solar and lunar positions has been linked together. It can be seen that the solar and lunar pairs are symmetrically placed about a point very close to the equinox solar date path. For the latitude of Bolton the actual point of symmetry will be at an altitude of 36°·15, and the symmetry will be exact with respect to angle and very nearly exact with respect to number of calendar days.

We will refer to the 36°·15 position on the noon radius line as the eclipse point. It is 0°·35, or about one calendar day, above the equinox position of the Sun. Once this phenomenon has been detected and the eclipse point determined from a few observations it will have explanatory and predictive value in future observations of eclipses. A lunar eclipse will occur whenever there is a full Moon at which the solar and lunar positions, translated back to the noon radius, are symmetrically placed about the eclipse point within approximately ± 1°·5. Angular symmetry about the eclipse point can be approximately determined by counting calendar days either side of it, so the 'opposition point' to the solar position can be found and the proximity to that point of the expected 'noon equivalent' lunar position at the full Moon can be measured. The nearer the solar and lunar positions are to symmetry the greater the eclipse. The error introduced by this counting method varies from zero for eclipses at the equinox to ± 0°·35 at the solstices. It is systematic, depending only on altitude on the noon radius line, and so with sufficient expertise it may be possible to apply a compensation factor. Alternatively, the addition of a true angular scale to the noon radius line is technically straightforward, although the benefit of it may not be intuitively obvious. If used, however, it would also make the measurement of the ± 1°·5 limit around the 'opposition point' to the solar position straightforward.

Experience of the usual movement of the lunar shadow across the calendar as illustrated in Fig. 3, together with a few observations in the days leading up to a full Moon, should enable the track of the lunar shadow in the hours either side of an imminent full Moon to be extrapolated on the calendar. The ± 1°·5 limit around the 'opposition point' is comfortably larger than the observational accuracy of ± 0°·014 which we have assumed, so the calendar should thus enable an observer to answer the question, "If there is a full Moon tonight, will there be an eclipse?", with a reasonable degree of accuracy. It should also be possible to predict roughly how much of the Moon will be eclipsed by observing how close the Moon will be to the 'opposition point'.

The accuracy of this method is dependent on knowing roughly when the full Moon will occur. Around the time of an eclipse the 'noon equivalent' position of the Moon on the sundial will change by about 1° each day because of the change in the Moon's ecliptic latitude, and by somewhere between zero and 5° each day because of the change in its ecliptic longitude. For eclipses occurring near the solstices the effect due to the change in the Moon's ecliptic longitude is at its least, and hence it is possible that the Moon's path will remain within a degree or so of the 'opposition point' for two or three days. In those circumstances it would be possible to be confident in predicting an eclipse even if one had only a vague idea of when the full Moon would occur, subject of course to the Moon actually being visible at the time when it is full. For eclipses near the equinoxes, however, the 'noon equivalent' position of the Moon can vary by more than 6° in a day. In those circumstances the Moon's path would only remain within the ± 1°·5 limit around the 'opposition point' for about 6 hours either side of the time when it crossed that point, and so it would be necessary to predict the time of the full Moon with an accuracy better than ± 6 hours.

Determining the time of the full Moon is likely to present difficulties to observers who have limited access to technology. The length of a lunar month varies up to ± 6 hours from the mean, so predicting the time of a full Moon from a previous eclipse is not particularly accurate. It is difficult to know how accurately the phase of the Moon can be determined directly by a naked-eye observer. Aristarchus seems to have been about five hours out in estimating the time of the half Moon for the purpose of determining the relative distances of the Sun and the Moon[9]. The half Moon is probably the easiest of its phases to judge, but unfortunately the length of time from the half Moon to the full Moon varies even more than the lunar month, by ± 20 hours from the mean.

The best method may be that reported by da Silva[10], who noted that in the period immediately before a full Moon the distance of the Moon above the horizon as the Sun sets can be used to give a good estimate of the time of the full Moon. If the ecliptic latitude of the Moon is near zero, as it will be around the time of an eclipse, then this method will be simpler and more accurate. If a full Moon occurred exactly at sunset, then an observer standing on level ground would see his or her shadow, made by the setting Sun, point directly towards the position on the horizon at which the Moon was rising. The mean change in the ecliptic longitude of the Moon in one day is 13°·2, so one day earlier the Moon would have been about 13° from that point on the horizon. If, therefore, there is to be a full Moon within the next 24 hours, one should be able to get a fairly good idea as to when it will occur by estimating the angle between the Moon and this point on the horizon at sunset. The diameter of the Moon itself can be used as a reference angle to help to estimate the time to the full Moon as a proportion of one day, reducing the risk of significant observational error. There are also, however, two small systematic errors in the method. The first will occur when the ecliptic latitude of the Moon is not zero. That error will be at its maximum for a full Moon occurring at sunset. When the Moon is 1°·5 from the ecliptic the error will be 3 hours at sunset and will fall to less than half an hour for full Moons which are more than 12 hours ahead. The second error is due to the observation being made topocentrically rather than geocentrically. That error will also be at its maximum, in its case 2 hours, for a full Moon occurring at sunset and will also fall rapidly for full Moons later in the night. In practice, the effect of these two systematic errors is fairly small. A simulation of using the method was conducted over 11 full Moons chosen at random, without regard to whether the Moon's ecliptic latitude was near zero or not. It gave a mean error of 1·5 hours and a maximum error of 3 hours, which are well within the tolerable limits.

For most eclipse possibilities an instrument of the type we have described should be able to answer the question, "Will there be an eclipse tonight?", with a good degree of accuracy, provided a few observations of the Moon have been made in the preceding days and the position of the Moon has been observed at sunset. It will certainly often be possible to answer the question very confidently, either in the positive or the negative, but there will be other occasions when the answer is less certain. If an eclipse is predicted to occur, the accuracy of the prediction as to when it will occur will depend only on the accuracy with which the exact time of the full Moon has been foretold, as the maximum of an eclipse occurs within about 15 minutes of the full Moon for partial eclipses, and within about 5 minutes for total eclipses.

The eclipse year

The method described above for using this instrument to predict lunar eclipses a day or two before they occurred would only require record keeping on the face of the sundial, with temporary markings superimposed on the permanent pattern of curves. The next level of sophistication would probably require a separate means of keeping a record, albeit a fairly simple one. Once it had been noticed that the angular distance, θ, of the 'noon equivalent' position of the Moon from the 'opposition point' is the key indicator as to whether or not the current full Moon will result in an eclipse, it would certainly be noticed that the variation in θ over successive full Moons is regular and periodic. The period of this variation is about a year and the amplitude is about ± 5°. Because of the regular nature of the variation it should be clear to a user of the instrument that keeping a record of it would be of value in predicting eclipses further ahead than just a day or two. Such a record is shown in graphical form in Fig. 5, for a period spanning 20 full Moons. Even for observers who did not have the benefit of being able to display this information as a Cartesian graph it should be possible, by suitable interpolation and with as little as two years' data, to estimate the period as being about 347 days with an accuracy of about ± 4 days. When we simulated the process of deducing the period with 15 years of data available we obtained a value within ± 0·3 of the actual value of 346·62 days.

It is of course the Moon's latitude at successive full Moons which is being displayed in Fig. 5. The mean period, 346·62 days, is the length of the eclipse

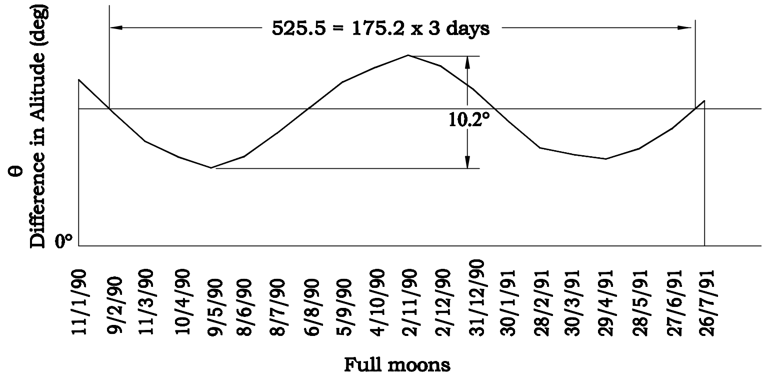

FIG. 5

The difference in altitude between the position of the Moon and the 'opposition point', which is the position symmetrical about the eclipse point with the solar position on the noon radius, plotted for full Moons between 1990 January and 1991 July.

year, the time which it takes the Sun to move between the points at which the Moon's orbit crosses the ecliptic. Those points, called nodes, correspond to the points where the graph in Fig. 5 crosses the axis. The eclipse year is the period which underlies eclipse cycles, and the ability to predict eclipses accurately depends on knowledge of the length of the eclipse year, the length of the lunar month, and the manner in which those two periods interact. An umbral lunar eclipse will occur when there is a full Moon within approximately ± 9 days of the time that the Sun is at a node, and a total eclipse will occur for a full Moon within ± 6 days[11]. These are termed the eclipse limits. The Sun passes through a node on average once every 173·31 days, the eclipse year being the time taken to pass through two successive nodes. Full Moons occur on average every 29·5306 days, so, if there were no variation in the lunar month and the eclipse year, after one lunar eclipse there would be another one $6 \times 29{\cdot}5306 = 177{\cdot}18$ days later, provided that that were still within ± 9 days of the Sun passing through a node. The difference between 177·18 and 173·31 is approximately 4 days, so the underlying pattern of eclipses is for them to move backwards by an average of 4 days in every six-month period, relative to the time when the Sun passes through the node, until the eclipse limit is reached.

There is, however, considerable variation in both the lunar month and the eclipse year. The time that it takes the Sun to move between successive nodes can vary by over 4 days either side of 173·31, and the length of six lunar months varies by up to 2½ days either side of 177·18. Exact eclipse prediction would therefore require a knowledge of the various periods which underlie the fluctuations in the lunar month and the eclipse year. However, if we make predictions about lunar eclipses using solely the mean values for those periods, ignoring the fluctuations, then the results we obtain would still be quite impressive for naïve observers.

Suppose observers had noticed the periodic nature of the angular distance, θ, between the Moon's position and the 'opposition point' to the Sun's position at successive full Moons and had decided to use that to predict all future occurrences of lunar eclipses. Let us assume that they had recorded a sufficiently long run of observations to give fairly accurate values for the mean eclipse year and the mean lunar month. Although the time between successive full Moons is a difficult observation to make, as noted above, the mean lunar month can be found quite accurately from the interval between two eclipses, the further apart the better.

The initial conditions needed to start the prediction are the dates of one full Moon and one time when θ is zero. We will use the eclipse at 4:44 a.m. on 2000 January 21 to give the date of a full Moon and the Sun's passing through a node on 2000 January 24 to give a date on which θ was zero. Note that in practice the latter would need to be obtained by interpolation from the data given in Fig. 5, as θ has no meaning as an observable quantity except at full Moons. The results of predicting the lunar eclipses for the following century are shown in Fig. 6.

The predicted full Moons and predicted times when θ is zero have been found by simply counting forwards in steps of the mean lunar month and half the mean eclipse year from the starting dates. The interval between the two has been plotted on the horizontal axis. The data for the actual eclipses are taken from those provided by Espenak[12]. Total eclipses are those with an umbral magnitude greater than 1 and partial eclipses have an umbral magnitude between 0 and 1. Those with an umbral magnitude less than 0 are penumbral eclipses, which are not easily detectable by the naked eye. It can be seen that an observer would be safe in predicting that there would be a total or very nearly total eclipse for any full Moon for which the predicted interval is less than five days. Between five and ten days the magnitude and likelihood of an eclipse decline rapidly, and for an interval of more than ten days it is unlikely that there would be a noticeable eclipse.

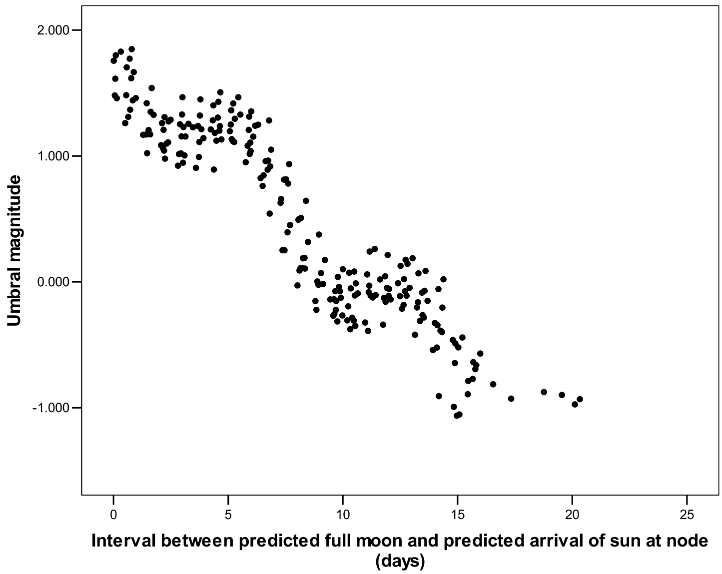

FIG. 6

Predicting lunar eclipses between A.D. 2000 and A.D. 2100 from the full Moon on 2000 January 21 and the time when the Sun was at a node on 2000 January 24.

Those would be quite satisfying predictions to be able to make for all future eclipse possibilities. More important, perhaps, would be that the instrument had enabled a theoretical framework to become apparent which explained the pattern of eclipses in terms of the interaction between two periodic phenomena. To deduce this solely from examining historical records of eclipse times would require a long run of data and, even then, would seem to present a significant challenge. Further, once the theoretical basis involving two interacting periods had been established, this would perhaps guide those who were interested to seek further refinement of the predictive model by looking for subsidiary periodic variations in the two phenomena.

Conclusion

This work has only involved computational simulation of the properties of a sundial. It may be that the actual construction of an instrument as described would reveal difficulties in its operation or the interpretation of its readings which have not been anticipated. However, the underlying principles appear sound and there seems to be no reason why an instrument with these capabilities, but possibly of a somewhat different design, could not be constructed from simple materials by people with no understanding of the Moon's and the Earth's orbits. This of course leaves entirely open the question as to whether, at some time, it has been done.

Acknowledgement

This work would not have been completed without the work of Dennis Shevelan, who carried out many of the original investigations and computational simulations for solar calendars constructed from simple materials, and on whose efforts this investigation has been built[13].

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REVIEWS

The Isaac Newton Telescope at Herstmonceux and on La Palma, by A. Wilson (Science Projects Publishing, Herstmonceux), 2010. Pp. 148, 23·5 × 15·5 cm. Price £10·95 (paperback; ISBN 978 0 9512394 2 1).

My handy *Concise Oxford Dictionary* gives one definition of 'saga' as a "story of heroic achievement or adventure", and I suppose that term might well apply to the tale of the *Isaac Newton Telescope* (*INT*), as told in this little book by Anthony Wilson. Well written, nicely illustrated, and a real bargain at under £11, it covers a fascinating piece of modern British astronomical history and should be on the book-shelves of anyone concerned with the progress of our science and especially with the chaotic state in which we find ourselves today.

Begun as a project to bring optical astronomy in the UK back into the front rank after the Second World War (to join radio astronomy and theoretical astrophysics), the *INT* was beset by problems from the outset, often to do with funding by the Government (which probably never really understood science while paying erratic lip service to it — a complaint we can level at it even more strongly today) but equally by the failure of the so-called community (or at least its leaders) to agree on a design and location for it. (For a detailed account of this phase of the *INT* story, see also Lee Macdonald's excellent article in *JBAA*, **120**, 73, 2010.) In the end, after 21 years of trials and tribulations, Queen Elizabeth declared the 98-inch *INT* open on 1967 December 1 on the less-than-perfect site of the relocated Royal Observatory at Herstmonceux (RGO).

One should remember, however, that the foreign travel we take so much for granted today was not so readily available during the 1950s and early 1960s when much of the planning took place, and neither was the international cooperation we rely on today to do our astronomy nearly so well developed; remember that Spain (which includes the Canary Islands) was still under the iron grip of General Franco until late 1975. And while we must acknowledge that the site was not ideal, Met Office cloud-amount records show that the strip along the south coast of England is about as good as it gets in the UK. The *INT* was definitely *not* down on the Pevensey Levels — it's on a hill and could be seen for miles around. And located there, it provided a first experience for many young British astronomers of a large telescope and a test bed for many new instruments. And, as readers of this *Magazine* will appreciate more than most, even in the British climate, a dedicated telescope with a dedicated observer can produce remarkable results (although not perhaps if cosmology is your 'thing'!).

However, from the early 1970s, and under the recently-formed Science Research Council (SRC, the first of the chameleon-like 'Research Councils' to control the purse strings of UK astronomy — to be followed by SERC, PPARC, EPSRC (briefly), CCLRC (also very briefly), CLRC, and now STFC), the knives were out for the RGO, as a dwindling budget forced the kaleidoscopic (and university-dominated) committees of the then-current Research Council to reduce spending, get 'value for money', 'top-slice' allocations, and do all the other unsavoury things that progressively emasculated the RGO, deflecting it from its rôle as a provider of fundamental astronomical services to the nation. And one of those 'things' was to turn the RGO into a workshop to provide the Northern Hemisphere Observatory (NHO), eventually to be sited on La Palma; the NHO has now, almost predictably, been abandoned. The really clever bit was to insist that the *INT* be transferred to the new site; this was to be astronomy's 'sacrifice', so that funds could be obtained against competition from other areas of science (but at the same time pulling at least one fairly big rug from under the RGO). Of course, with a new mirror, a new dome, a large amount of new ironmongery to adapt to the new latitude, and a suite of new instruments, it would have been no more expensive to provide a completely new telescope, leaving the original *INT* to carry on a solid programme of work at Herstmonceux — it was absurd to think otherwise. I don't suppose we shall ever know for sure whether the extinction of the RGO was definitely on the cards at this stage; was it conspiracy or chaos?

Whatever the truth, the *INT* had a new lease of life on La Palma, and Wilson gives some nice examples of the work done by the international teams of observers who have used it there. As to the future, will there be any further British use of the telescope? Would we have been better off soliciting funds from bonus-laden bankers rather than rely on money from a scientifically ignorant and parsimonious Government? It would be nice to think that a future edition of Wilson's excellent book would have a 'happy ending', but I fear not! — DAVID STICKLAND.

Watchers of the Stars: The Story of a Revolution, by P. Moore (Horwood Publishing, Chichester), 2009. Pp. 186, 24 × 16 cm. Price £20 (hardbound; ISBN 978 1 904275 36 7).

One cannot embark upon a review of a book by Sir Patrick Moore without first paying tribute to the author, who is not only a living legend but also, to use a colloquialism of his youth (and mine), a Good Egg and a man whose coruscating enthusiasm has infused so many with a passion for astronomy.

His book recounts the lives and astronomical discoveries of Copernicus, Tycho Brahe, Kepler, Galileo, and Newton, and describes how it came to pass that between them they transformed the accepted belief that the Universe was centred on the Earth into a perception that the Earth was one of several planets revolving around the Sun. The emphasis throughout is the extent to which this amounted to a revolution in human understanding, and the formal refusal of the Catholic Church to accept Galileo's realization that the Earth moves or even allow his arguments to be published is in a sense the climax of the story.

In this connection it is interesting to note that this is the third edition of Sir Patrick's book, the first edition having been published in 1974 and the second in 1994, and it is only with this edition that he can complete the story, inasmuch as it was not until 1982 that the Pope at last set up a commission to review the Catholic Church's dealings with Galileo, which led in 1992 to the formal acceptance of the Earth's position as a planet and the annulment of Galileo's conviction for heresy, and finally in 2000 to a formal apology on behalf of the Catholic Church for its treatment of him.

The story is told lucidly and briskly, with a satisfactory amount of biographical detail, and within the first chapters a brief summary of our present understanding of the Solar and Galactic Systems and of what had been thought and written about the Earth in space prior to the arrival of Copernicus. The breathtaking perception of Aristarchus in suggesting as early as *c*. 260 BC that the Earth was one of several planets moving round the Sun, and the astonishing achievement of Eratosthenes in accurately assessing the diameter of the Earth in *c*. 240 BC are of course mentioned, and the stultifying effect upon astronomy of Aristotle's conviction that the Earth was not in motion, given the veneration with which his views were for so long afterwards held, is made clear.

The book, then, is a well-told tale of five heroes and a villain, the latter being Pope Urban VIII, the man who forced Galileo to recant and secured his conviction for heresy. As Cardinal Barberini, he had been a friend to Galileo, discussing with him and apparently even accepting many of his ideas, and the author finds it hard to accept or fully understand this change of heart. In the author's words, he has "gone down in history as a treacherous bigot"; but the difference in the respective responsibilities of a Cardinal and a Pope is surely an adequate explanation.

Religion is more important to more people than astronomy. This is not necessarily a good thing but it is a fact, as is the need of religion for sure belief rather than changing comprehension. A religious leader must uphold the tenets of his faith, and the Pope's responsibility for maintaining the Catholic Church's doctrines, according to which Galileo's teachings were clearly heretical, left him no option but to act as he did. Once confrontation had been set up, any hint of acceptance by the Church would have given rise to uncertainty, bewilderment, and confusion among the faithful for whose spiritual welfare the Pope believed he was responsible, and could even have led to another of the schisms which have plagued Christianity and other religions down the ages, as is evidenced by the current doctrinal dilemmas of our own Archbishop of Canterbury. As Sir Patrick makes clear, Galileo was not treated harshly by 17th-Century standards in his subsequent 'house arrest', and despite the verdict of history I cannot but feel that Galileo brought his fate upon himself, his brilliant mind and enthusiasm for the unfettered dissemination of observed reality blinding him to the position he was forcing upon his old friend.

Sir Patrick's book can be heartily recommended for its clear and concise narration of the events which led to the general acceptance of the Sun's centricity in the Solar System, and for highlighting a classic confrontation between reality and religious belief. I noticed one misspelling — a reference to "the precision of the equinoxes"; though now I come to think about it they are fairly precise — but overall the book is well produced, with copious illustrations and a particularly appropriate laminated front-cover design, and I found it a pleasure to read. — COLIN COOKE.

Sky, by Storm Dunlop (The Guild of Master Craftsmen, Lewes), 2009. Pp. 160, 25 × 25 cm. Price £14·99 (paperback; ISBN 978 1 86108 660 0).

Storm Dunlop collates here a broad selection of photographs portraying the sky as viewed in various parts of the world, at different times of day or night, and in different meteorological conditions. The topics that motivate the photographer tend to be the sensational — vivid dawns and dusks, rainbows, aurorae, approaching tornadoes, or electrical storms — but there are messages to be read in the gentle cirrus clouds too, and there are aspects worthy of study in them all. The text is minimal: apart from a short introduction, only the briefest of explanations is given to each picture, but sufficient nevertheless to identify the arresting feature and (often) its interpretation. Different chapters deal with clouds, weather, phenomena, storms, dawn and dusk, and the night sky. Only a few of the pictures are the work of the author, but a full list of sources is given.

One sees many vivid hues in the sky, often fading very rapidly as a Sun–cloud alignment alters, and they are the more interesting when one can understand what one is seeing and how to interpret it. This book is an excellent source of that information, the more so because it illustrates so lavishly what cloud formations can tell us; the only small piece of information which I wished had been more complete was the place name or location of each photograph. It is hard to tell just how faithful to the original these photographs are, yet that is only a secondary consideration. The clouds have structure as well as colour, and it is that structure which has the greater physical significance; many of the colours that one may glimpse are kaleidoscopic — the chance products of angle and aspect.

The book has a soft cover, and that doubtless keeps the price down, but I am not sure that it necessarily serves the book well. The publisher's blurb is a bit puzzling; it describes the contents as detailing wonders of the constellations, meteors, and the Moon, and suggests that it contains pictures of shooting stars, but those are one topic which the book does *not* cover. The publisher also calls the book "an inspiration for every keen sky watcher", but I would rather recommend it for the converse reason: having leafed through this book, you are much more likely to *become* a keen sky watcher — a fitting conclusion to IYA.

This is a fine picture book to dip into, and can be warmly recommended for people of all ages and persuasions. — ELIZABETH GRIFFIN.

The Caldwell Objects and How to Observe Them, by M. Mobberley (Springer, Heidelberg), 2009. Pp. 302, 23·5 × 17·5 cm. Price £24·99/$34·95/€34·95 (paperback; ISBN 978 1 4419 0325 9).

This book, as expected, is primarily concerned with the description and details of the Caldwell objects and these are covered to the depth suitable for an amateur astronomer. There is also a section on the compiler of the Caldwell list, Sir Patrick Moore, as well as primers on observing and imaging in general, although these are not covered in any depth. Whilst they will provide the novice with some guidance, the reader will have to go elsewhere for a comprehensive guide.

The book puzzles me slightly; I'm unsure if I should be using it as a reference book, a book to help plan an observing session, or if I should take it to bed and read it from cover to cover. It sets out to be a reference book, with consistent levels of information on all the objects. It has a good index but no summary tables. Used as an observation-planning aide it is likely to become tiresome because of the lack of tables; the reader will have to flick through many pages to find what objects are suitable for their equipment and location, or use the inside back cover to make their own tables.

The basics for each object are covered on a single page, such as position, brightness, suggestions for finding the object, and the best time of year to observe. The author also recommends the best aperture and filters for observing and provides good comprehensive descriptions. A second page for each object is used for charts and images (generally from amateur astronomers). The author's personality and humour does come through in his writing, making the book an easy and enjoyable read (I particularly like Caldwell 8 where the author describes all the great open clusters in Cassiopeia before describing C8 as "less than mind blowing").

You might be forgiven for thinking that this book is all you need (apart from a telescope!) to begin observing the Caldwell objects. However, the charts provided are not suitable for finding the objects, and this is pointed out by the author. Despite their low quality and small size, the charts do provide the reader with the general location in the sky and for this they are useful. The charts contain a number of objects and are only printed alongside the first object described and it quickly became irritating having to flick back to previous objects to look at the associated chart, especially when there is ample space for the chart to be repeated for most objects.

For £24·99 I would not buy this book, but if cheaper or given as a gift I would happily add it to my collection. — SIMON DAWES.

Viewing the Constellations with Binoculars, by B. Kambič (Springer, Heidelberg), 2009. Pp. 518, 25·5 × 17·5 cm. Price £22·99/$39·95/€39·95 (paperback; ISBN 978 0 387 85354 3).

Binoculars are a handy part of any astronomer's armoury. Compact, relatively light, and easily transportable, they provide eye-filling views of star fields, nebulae, and comets, while also offering a touch of magnification to resolve clusters and wide doubles. Hence, a book such as this, subtitled "250+ wonderful sky objects to see and explore", will attract the attention of many a skygazer. However, this is much more than a binocular tour of the sky, as its length of 500-plus pages suggests. In fact, around a quarter of the book is taken up with a primer on general astronomy, including stellar evolution and cosmology. I expect that many potential readers will wonder, as I did, how much of this material is truly necessary in a book supposedly aimed at users of 10 × 50 binoculars.

It's on page 172 that the action finally starts, visiting 69 constellations (by my count) visible from mid-northern latitudes. Observers in the British Isles will be unable to see the most southerly of them but there are still plenty of targets to relish, ranging from the brightest galaxies, nebulae, and clusters to challenging doubles and variables. Each constellation is illustrated with a modest star chart, with more detailed finder charts for specific objects. As a key to the excitement level of the various objects, a cartoon observer is depicted either boggling through his eyepiece, sitting thoughtfully on his stool, or lying face down on the ground having apparently dozed off. The descriptions are extensive and the level seems suited to advanced amateurs rather than beginners.

The author, Bojan Kambič, is a Slovenian amateur who has written, illustrated, and translated the book himself. It is undoubtedly an impressive achievement, but various slips and linguistic infelicities ("Beeheve" for "Beehive" and the persistent mis-spelling of Melotte were two that particularly grated) betray the need for an editor and proof-reader. As if to underline this, the book ends with a list of basic objects for beginners, in which the page references are all given as "xxx". While there is enough here to satisfy an observer for many years, and one which I look forward to using extensively, a tighter focus on the topic, with more attention to editing and proofreading, could have turned this into a much better book. — IAN RIDPATH.

Countdown! Or, How Nigh is the End?, by P. Moore (The History Press, Stroud), 2009. Pp. 187, 20 × 12·5 cm. Price £9·99 (paperback; ISBN 978 0 7524 5222 7).

There is, perhaps naturally, something in human nature that makes us want to know the future, and some people, it seems, are willing to believe anything, especially if it involves the end of the world. I wonder how many 'significant dates' there have now been at which dire events have been predicted to happen? All (so far at least!) have passed without the prediction being fulfilled, but this never seems to stop some people believing the next prediction. Perhaps the favourite predictions are the Second Coming of the Messiah (although the *Bible* tells us explicitly that no man knows the day or the time), and, more generally, the End of the World, and favourite dates have been the two millennia. In this book, first published in 1983, Patrick Moore gathers a collection of some of the more famous and bizarre predictions and recounts their histories with suitable irreverence. For example, in the USA, one William Miller became obsessed with the *Old Testament* book of Daniel, and came to believe by 1832 that the Second Coming would be in 1843, probably at midnight on March 21. The major Leonid meteor storm in 1833 helped to confirm his belief! He spread the word widely, and gathered many followers, changing the date twice when nothing happened either on March 21, or on any other date in 1843. Widespread panic died away, but he does not seem to have been blamed for the failure of his prediction.

Many other examples of misguided predictions are given in the book, from Augustine (who believed the world would end in 1000 AD — but could not live to test this, since he lived in the 6th and 7th Centuries) to Maria Khristos in the Ukraine in 1993. In the 1840s, Lady Hester Stanhope (a niece of William Pitt) took two white horses to the Mount of Olives in response to a prediction that Jesus would appear there — one of the horses was for Jesus and the other for her. (She had earlier settled in the Middle East, where she had been visited in the 1830s by Alexander Kinglake, an intrepid English traveller and (anonymous) author of the 1844 travel book *Eothen*, who gives an interesting account of her isolated life in a Syrian fortress.) Of course, astrologers have also been active in making predictions, perhaps the most famous being Nostradamus in the 16th Century — but even in the 20th Century astrological predictions have been used by governments to determine dates for elections.

Comets have long been regarded as harbingers of doom, and here we approach the realms of science — for impacts of comets and meteorites of sufficient size could indeed wreak havoc. Despite many misunderstandings about the influence of other bodies in the Solar System (including some who believe that the Moon is actually getting closer and will collide with the Earth), there are some real dangers, that are explored in this book. Moore also discusses the inevitable topic of aliens and flying saucers, reminding us of the panic caused by the rather-too-realistic radio presentation of H. G. Wells's *War of the Worlds* in 1938. Throughout the book, Moore is at pains to debunk bad science and groundless predictions, and to explain what the genuine science is (although — p. 148 — he is clearly not a believer in human-induced global warming). He concludes the book by an account of the genuine 'end of the world', which will happen when the Sun becomes a red giant and the Earth spirals into it. Having published a paper on that very topic, I was somewhat critical of the details given here (the timescale for the oceans to boil is too long by a factor of about 3, and the maximum radius given for the Sun is too small by a similar factor), but he gets the essence right — the ultimate fate of the Earth is to be destroyed by the Sun in the normal course of its evolution.

The danger of updating a book is that bits of it fail to get updated, and sadly that has happened here in quite a number of places — for example (p. 148), the solar-neutrino 'problem' is still presented as it was at the time of the first edition. In other places (*e.g.*, the end of Chapter 1 and the beginning of Chapter 2), it looks as though the updating was done about 1999 or 2000 rather than in 2009. There are also rather too many typos (I counted about 20 without really trying), and it's a pity that the scale on the H–R diagram in Plate 27 is badly misaligned with the diagram itself, making the Sun appear to have a luminosity of less than a tenth of its actual value, and has the decimal points in the wrong place (*e.g.*, 00·1 instead of 0·01). However, these are relatively minor quibbles and the book is certainly entertaining reading which manages to put across some proper science in the process. Maybe a suitable Christmas present for a not-too-credulous relation! — ROBERT CONNON SMITH.

Theory of Orbit Determination, by A. Milani & G. F. Gronchi (Cambridge University Press), 2009. Pp. 382, 25·5 × 18 cm. Price £45/$75 (hardbound; ISBN 978 0 521 87389 5).

The discovery of the first minor planets posed a major challenge to astronomers in the opening years of the 19th Century: how to determine an accurate orbit for a newly-discovered asteroid from a handful of irregularly-spaced observations spanning only a few weeks, so that the object can be found again months or years later. The problem was taken up in 1801 by a 23-year-old German mathematician named Carl Friedrich Gauss. His elegant new method, published in 1809, became the standard technique for determining the orbits of comets and asteroids.

Today, the database of the IAU Minor Planet Center contains orbits for almost half a million asteroids, and thousands more are added each month. A growing realization of the dangers posed to the Earth by the impact of an asteroid or comet fragment has led to the creation of projects such as LINEAR and Spacewatch to detect and track the many thousands of objects which could hit the Earth. As a result, the theory and practice of orbit determination remains an active area of research in dynamical astronomy, two hundred years after Gauss. The group led by Andrea Milani at the University of Pisa has made many significant contributions to the subject in the past thirty years. Their collected experience is the basis of this new book by Milani and his colleague Giovanni Gronchi.

The book begins by establishing the basic principles of dynamical astronomy, linear algebra, and the theory of least squares. Then the authors turn to several current problems of 21st-Century orbit determination. The first is the problem of identification. Next-generation sky surveys such as Pan-STARRS, using gigapixel cameras on 2-metre telescopes, will generate huge numbers of astrometric observations of small, rapidly-moving objects. How can these data be analysed automatically to identify observations of the same object made at different times? Milani and Gronchi describe techniques which allow up to 97% of objects in simulated next-generation-survey data to be identified successfully. Once a preliminary orbit has been determined for an object which could potentially hit the Earth, the next problem is to assess the probability of an impact in the future. The authors explain how the threat posed by a newly-discovered near-Earth object can be estimated using techniques such as simulations of swarms of 'virtual asteroids' and the method of minimum orbit-intersection distance.

The last third of the book addresses the theory of orbit determination applied to spacecraft. It opens with a detailed mathematical description of the gravity field of a planet and its effect on an orbiting spacecraft. This is followed by a very comprehensive chapter on non-gravitational perturbations, which includes a fascinating case study of the effect of solar radiation pressure on a spacecraft orbiting an asteroid. The radiation pressure and the gravitational pull of the asteroid are of similar magnitude, and the geometry of the resulting orbit is quite unexpected!

In the closing chapter, Milani and Gronchi present an extended case study of ESA's proposed Mercury-orbiter mission, *BepiColombo*. They explain how orbital tracking of the spacecraft will be used to explore the internal structure of the planet and its rotation, and also — surprisingly — to test the General Theory of Relativity. The practical applications of the theory of orbit determination have come a long way in the two centuries since Gauss.

In conclusion, this book is a lucid and comprehensive survey of exciting new developments in an old area of astronomy, written with enthusiasm and authority by two astronomers who have made significant contributions to its renaissance. The book assumes no prior knowledge of celestial mechanics, and it should be accessible to anyone with a graduate-level knowledge of maths or physics. — DAVID HARPER.

The Authenticated Meteoritic Falls of the British Isles: A Compilation with Additional Notes and Photographs, by James D. Robinson (published by J. D. Robinson, 10 Bewick Crescent, Newton Aycliffe, Co. Durham, DL5 5LQ), 2009. Pp 147, 23·5 × 15·5. Price £5·49 (plus £2 post & packing) (paperback).

Meteorites are the astronomical equivalent of manna from heaven. They are a gift from the Solar System. Instead of having to employ extremely expensive spacecraft to travel outwards and then return to Earth with samples of asteroids, or Martian or lunar material, we simply watch out, and these samples rain down on us from above.

The first recorded meteorite 'fall' in the British Isles was at Wold Cottage, near Bridlington, in Yorkshire. The local population were so taken by the strangeness of the event that they erected a brick obelisk in commemoration. At that time, in 1795 December, the scientific opinion was that these stones had flown through the atmosphere from a relatively nearby volcano!

Twenty-one British Isles falls have been witnessed since then, one per decade, a rather paltry influx rate since it has been calculated[1] that a meteorite actually hits the British Isles, on average, every three weeks. If our weather was not so appalling and our country so littered with rocks, this book would have had to be considerably longer.

James Robinson describes each fall in impressive detail and has scoured national and local newspapers for reports of these events — the *Caernarvon & Denbigh Herald*, the *Hinckley Times*, the *North Wales Chronicle*, the *Dundee Advertiser*, the *Wigan Observer*, the *Ballymena Weekly Telegraph*, the *Newcastle Daily Chronicle*, the *Wellington Journal*, the *Derry Standard*, the *Perth Courier*, the *Bucks Gazette*, the *Limerick Chronicle*, the *Glasgow Herald and Advertiser*, even *The Oracle*, *The Scotsman*, and *The Times* — little has been overlooked. These reports have been reproduced verbatim. Robinson concentrates on eye-witness accounts, the opinions of the general public, the views of the local clergy, medics, and gentry, the ideas of curators of local museums, and the conclusions of contemporary scientists. The more detailed mineralogy is left to weightier tomes[2].

I loved the stories of the folk who scoured the local countryside for samples. I revelled in the squabbles over ownership. I marvelled at the fact that nobody was injured and little property was damaged. This book is an absolute joy. It is well researched, well referenced, and eminently readable. — DAVID W. HUGHES.

References

(1) D. W. Hughes, *Space Science Reviews*, **61**, 275, 1992.
(2) A. L. Graham, A. W. R. Bevan & R. Hutchison, *Catalogue of Meteorites, Fourth Edition* (*Revised and Enlarged*) (The British Museum (Natural History), London), 1985.

The Scientific Exploration of Mars, by F. W. Taylor (Cambridge University Press), 2009. Pp. 348, 25 × 19 cm. Price £30/$45 (hardbound; ISBN 978 0 521 82956 4).

Professor Fred Taylor needs no introduction to readers, and here he explores the way in which our understanding of the Red Planet has grown logarithmically with time, largely through spacecraft missions beginning in the 1960s. Following a brief description of our knowledge up till the Space Age, each mission is described in considerable detail, with plenty of illustrations. We should note in passing that Ormsby MacKnight Mitchel's observatory has mysteriously displaced Percival Lowell's on page 10.

Taylor has some nice personal anecdotes in the footnotes, and several made me smile (especially on page 15, where the spectroscopic discovery of H_2O on Mars is discussed). He concentrates upon current and most recent exploration, with all the essential background details such as the biological experiments, our understanding of geological history, climate change, and modelling, *etc*. The history of the various agencies involved in the missions is also detailed, whilst the membership of the Mars Study Groups forms a useful Appendix. Taylor's text is extremely informative, and has already proved to be a valuable source of reference in my own Mars library.

Taylor ends his book with a report of a hypothetical manned mission to Mars in 2038, and this enables him to speculate rationally about the likely way forward. He thinks that humans will leave their footprints on Mars before the end of the present century; I do hope so, as it already seems such a long time since 1969! Even if Mars should prove sterile, it will be, he writes, a valuable outpost in keeping alive the dream of space exploration.

Highly recommended both to the specialist Mars researcher and the casual reader. — RICHARD MCKIM.

Physics of the Sun: A First Course, by D. J. Mullan (CRC Press, Abingdon), 2010. Pp. 360, 24 × 16 cm. Price $79·95 (about £50) (hardbound; ISBN 978 1 4200 8307 1).

The enormous advances in our knowledge of the Sun in recent years might seem overwhelming to any student or indeed established worker in solar physics, and it takes a lot of courage, not to mention research in published papers, to write a textbook on the subject aimed at postgraduate students. This is what Dermott Mullan has done in this very reasonably priced and compact book. He has in addition taken the approach of setting the student some searching questions at the end of many of the chapters, which if followed should make any student enthusiastic in this field become a real expert, conversant with fundamental concepts of the physics of our nearest star. The book is aimed at American students, who may have more time to delve into these problems than their counterparts in the UK, where sadly universities are compelled by financial restraints to push their graduate students through in a space of just three years. When you read this book and see the questions, you really get a feeling for how much British students are often missing in their understanding of physical principles.

The eighteen chapters cover nearly all relevant aspects of solar physics, from the solar interior to the solar wind. There is a slightly unusual first chapter discussing fundamental parameters, which include the Sun's shape and critical frequency for global oscillations. Rather than take the expected route from solar interior outwards, Mullan starts with the photosphere, with standard discussions on radiative transfer, opacity, and ionization over the next three chapters, culminating in an extensive chapter on modelling the photosphere. The solar interior is discussed over several chapters, including fairly standard ones on energy generation and radiative and convective parts, but with also some up-to-date reviews of solar neutrinos and helioseismology. For this reviewer, the section on polytropes revived mixed memories of tedious undergraduate lectures, so it was somewhat reassuring to read that they are after all relevant, if more for low-mass stars and white dwarfs than the Sun.

Things get a little more compressed in discussions of the chromosphere, corona, and solar wind. Sunspots, solar flares, and coronal mass ejections are included in these chapters rather than a separate discussion about solar activity. Coronal heating, which is after all a huge problem in solar as well as stellar physics, is allocated four pages, with Parker's nanoflare mechanism not getting a mention. Nevertheless, most of the relevant points are discussed, if only in outline.

Perhaps the biggest gripes relate to some out-of-date illustrations that would be very easy to rectify in future editions of the book. The ionization-equilibrium diagram on p. 289, for instance, has been replaced many times over, most recently in 2009. It was surprising to see that the *SOHO* spacecraft is placed at a point "where the gravitational pull of the Earth is comparable to the gravitational pull of the Sun": time to look at Lagrangian point definitions in our celestial-mechanics textbooks! The illustrations are generally clear, with copies of some of the less-clear black-and-white diagrams in a colour-illustration section.

This book will certainly serve as a standard textbook for solar and stellar students embarking on their Ph.D. degrees, though there is at least one big competitor in the market recently revised. It is clearly written with plenty of object lessons to illustrate physical principles. — KENNETH J. H. PHILLIPS.

Asteroseismology, by C. Aerts, J. Christensen-Dalsgaard & D. W. Kurtz (Springer, Heidelberg), 2010. Pp. 866, 23·5 × 15·5 cm. Price £90/$129/€99·95 (hardbound; ISBN 978 1 402 05603 5).

Asteroseismology is, according to the authors, our modern music of the spheres. The idea is that a star (or a star model) can have a very large number of normal modes, radial and non-radial, with anything from one node to a thousand, belonging to three categories — p (pressure as the restoring force), g (buoyancy or gravity as the restoring force), and f (surface waves). At the presently-available level of micro-magnitude and 1 cm s^{-1} in brightness and radial velocity, respectively, not all stars oscillate. But the Sun does and was the first to be studied in detail, beginning with work by Robert Leighton in 1961, though the word helioseismology seems to date back only to 1979. From the beginning, the news was cautiously good. The frequencies and amplitudes of many modes in concert probe the speed of sound in the deep interior, and conventional models of the Sun turned out to be nearly enough correct about density, temperature, helium fraction, and rotation rate as a function of radius to render their predictions of solar neutrino flux reliable and in disagreement with experimental data, thus tossing the problem into the laps of the weak-interaction physicists. A handful of other similar stars have cautiously revealed similar, though much less rich, spectra.

Stellar oscillations have also been modelled and seen for an assortment of main-sequence A and B stars, pre-main-sequence and evolved stars (I happen to be fond of the RV Tauri type), binaries, and white dwarfs. The situation for neutron stars is less clear, and in no case does the combination of theory and observation suffice to determine interior equations of state to address, for instance, the existence of pion condensate or strange matter near the centre.

The volume is very rich in data, graphs, equations, references (about 125 pages of them), specific examples, and hopes for the future, but it is not entirely easy to navigate. For instance, the index entry under white dwarfs, for the GW Vir and PG 1159 types, takes you to pp. 113–117, with no indication that the individual stars are analyzed on pp. 646–651, where it is revealed that the two names designate the same star, which has the richest assortment of identified frequencies, after the Sun. That GD 356 = V777 Her, the prototype of the variable DB stars, also takes a bit of snooping. It helps in mode identification that these stars aren't doing much else. In contrast, even long data streams for a few Wolf-Rayet stars have not permitted separation of changes in wind structure from pulsational behaviour. Not surprisingly, the authors end with hopes for the *CoRoT* and *Kepler* missions (now in orbit) and the anticipated *BRIGHT*, *PLATO*, and *Solar Orbiter*, as well as for ground-based networks and South Pole stations that could also produce very long data streams in brightness or radial velocity. If a topic with as much mathematical intricacy as asteroseismology were telling us about dark matter and cosmology, the community would be beating a path to its door. — VIRGINIA TRIMBLE.

Massive Stars: From Pop III to GRBs to the Milky Way, edited by M. Livio & E. Villaver (Cambridge University Press), 2009. Pp. 241, 25 × 18 cm. Price £70/$120 (hardbound; ISBN 978 0 521 76263 2).

This well-produced book includes some of the invited talks presented at the Space Telescope Science Institute Symposium held in 2006 May. There is no mention of the other invited talks, any contributed talks, posters, or discussion or summary, which makes it hard to get a feel for the meeting — the "attempt to capture all the aspects involved in the astrophysics of massive stars" referred to in the Preface. On the plus side, the authors have been allowed more space than in most other volumes of proceedings, so the papers here often run to more than 20 pages and have extensive bibliographies. Most of the volume covers a few major topics: massive-star formation and environments, stellar winds, eruptive mass loss, and supernovae.

The formation of massive stars is less well understood than that of low-mass stars, and observations are much sparser owing to their relative rarity and greater distances, but there is progress on both fronts, as described in the contributions by Krumholz, Elmegreen, Patel, Figer, and Townsley. The significance of outflows in the formation of the most massive stars is repeatedly emphasized. The maximum stellar mass found from modelling still falls far short of those observed in the Galactic Centre, but there remain physical processes that the current generation of models ignore and, as Krumholz remarks, the inclusion of almost every additional process reveals new and unexpected phenomena. The drive is coming from the wealth of new observations in the X-ray, IR, and submillimetre, many reviewed here. Star-formation environments, especially clusters, and their influence on the IMF are discussed in several contributions.

Kudritzki & Urbaneja end their substantial review of the determination of basic parameters and the winds of hot massive stars with the warning that the exceedingly low O-star mass-loss rates being derived from P V lines observed with *FUSE* depend critically on the assumption that P^{4+} is the dominant state, which was not supported by their test calculations and requires detailed investigation. Even the modestly lower mass-loss rates derived with allowance for clumping may be insufficient to remove enough O-star mass to make a WR star, and Smith discusses alternatives, including LBV eruptions.

There have been several massive-star meetings more recent than this one and whose proceedings have been published already, including the latest IAU (beach) Symposium 'Massive stars as cosmic engines' (see **129**, 40, 2009 for a review). This raises the question as to whether the reviews here may have been superseded in the other proceedings, but comparison of the volumes shows no material overlap. This collection complements the other proceedings and its concentration on a few selected topics makes it a good addition to 'Massive Stars' libraries. — PEREDUR WILLIAMS.

The Starburst–AGN Connection Conference (ASP Conference Series, Vol. 408), edited by W. Wang, Z. Yang, Z. Luo & Z. Chen (Astronomical Society of the Pacific, San Francisco), 2009. Pp. 474, 23·5 × 15·5 cm. Price $77 (about £50) (hardbound; ISBN 978 1 58381 696 7).

This hefty tome (474 pages) gives a comprehensive summary of the field of the starburst–AGN connection *via* papers given at a conference held in the charmingly named Shanghai Normal University.

The topic is very timely, given the increasing effort going into understanding the link between starbursts and AGN. It's somewhat of a chicken-and-egg-type question as to what comes first: central-black-hole activity or star formation in the host galaxy? This is a very complex issue, hampered by our very limited understanding of how the central black hole came to be there, how and when it grew, and what it does while growing. Star formation on the large scale, which can involve thousands of solar masses a year in extreme cases, is, dare I say it, better understood but only on a relative basis. The linkage between the two processes using feedback/triggering is the main theme of this volume, involving mostly longer-wavelength observations coupled with theoretical models. The advent of mid-IR (particularly *Spitzer*) and more-sensitive millimetre-wave facilities are clearly making their mark, and this is a research area that should benefit greatly from *ALMA* and *JWST*.

The contents are as one would expect, with topics ranging from local examples of the starburst and AGN phenomena to the more-distant lower-signal-to-noise-ratio Universe. Most of the papers are quite short with the occasional longer review-type to set the scene. As ever, one wonders about the virtue of many, many short papers. Acronyms were also well represented. I'd not come across 'DOGs' before (Dust Obscured Galaxies).

The conference was attended by over 100 researchers, most of whom had the chance to present their work. It's great to see a meeting with so many relatively junior people presenting alongside the more established figures. That aside, this is a fairly standard conference proceedings of most use to those working in the field, but it should also be in libraries. — PAUL O'BRIEN.

An Introduction to Relativity, by J. V. Narlikar (Cambridge University Press), 2010. Pp. 363, 25 × 18 cm. Price £70/$120 (hardbound; ISBN 978 0 521 51497 2), £30/$50 (paperback; ISBN 978 0 521 73561 2).

This is an update of Jayant Narlikar's relativity textbook originally published in the 1970s. It is mostly devoted to General Relativity, with a short section on Special Relativity. This market is pretty well covered by textbooks, so one looks for something which makes it stand out from the crowd. I think here there are a number of things which are done quite nicely — the worked examples and end-of-chapter problems are good, and they raise some interesting new points in places, so merit study. Another nice feature is the helpful warnings punctuated with exclamation marks when something is puzzling or counter-intuitive. There are a few instances of nice insight too, *e.g.*, on the non-linearity of gravity. The Special Relativity is fine if you already understand Special Relativity, but does not stand on its own as it is far from comprehensive, and a number of concepts are introduced without full explanation; but this is not a major problem, as the focus of the book is definitely General Relativity. This is explained very clearly, and more step-by-step. There are other texts which give a little more help in doing the calculations, some of which can be quite time-consuming, but for which there are useful shortcuts for metrics with a great degree of symmetry. Some of the more advanced topics (such as black-hole thermodynamics, Kerr metric) are sketched out rather than investigated in full detail, which is probably a sensible approach for this book; the alternative approach has its value, but then it would be a rather different book.

As is standard, cosmology is covered, and this is the only part of the book which falls short, in my view. The update has left a number of topics in observational cosmology (such as number counts, sizes) which are a little dated, and largely misses out the huge advances in understanding from studies of the microwave-background power spectrum, as well as the influential supernova Hubble diagram. Since there is a substantial discussion of alternatives to the Big Bang theory, it is curious to omit discussion of microwave-background data which provide the strongest evidence in support of the standard cosmological model. With this caveat, this is a very readable and accessible text on General Relativity, which advanced undergraduates will find enjoyable and not too overpowering. — ALAN HEAVENS.

Bayesian Methods in Cosmology, edited by M. P. Hobson, A. H. Jaffe, A. R. Liddle, P. Mukherjee & D. Parkinson (Cambridge University Press), 2009. Pp. 303, 25·5 × 18 cm. Price £40/$65 (hardbound; ISBN 978 0 521 88794 6).

Lewis Carroll was a mathematician by profession, which probably explains Humpty Dumpty's famous quote: "When I use a word, it means what I choose it to mean...". The word Humpty Dumpty clearly had in mind was 'probability', which started life as a simple statement about the frequency of some outcome in a large number of repeated coin tosses, *etc*. But today the word is increasingly used in the Bayesian sense, to denote degree of belief in a proposition. Belief is of course an individual matter, so Humpty Dumpty's probabilities will not be the same as yours or mine, and this seems to lead nowhere. But remarkably, a consistent apparatus can be erected on this unpromising foundation. You and I might have different views about the probability of life on Mars; but if a rover experiment returns a biological signal with only one chance in 100 of arising *via* instrumental noise, we can agree that life is 100 times more likely than it was before. The trouble is that, if you had a prior belief that life on Mars was impossible, no amount of experimental data will change your stance. This lack of a final probability of life on Mars that everyone can agree on is a controversial feature, but the Bayesian framework does have some major advantages, notably the fact that probabilities can be discussed for unique events, without the need to consider repeated trials. More generally, the Bayesian framework exposes clearly the assumptions and issues involved in inference (finding values for the parameters of a given theory in the light of data) or model selection (deciding which theory to prefer in the light of data). For those reasons, cosmologists have been particularly attracted to Bayesian methods. This volume is based on a meeting devoted to the subject, which took place in Sussex in 2006.

The book is divided into 13 articles, roughly equally split between fundamentals and applications, and some of these are more useful than others. There is a nice introductory overview by Skilling, although on the fundamentals of the subject it is hard to beat the treatment in David MacKay's textbook, *Information Theory, Inference, and Learning Algorithms*. The real value of the book for professional researchers will be in the articles devoted to numerical issues, since it is here that cosmology generates practical problems to be solved. With theory parameter spaces of fairly high dimensionality (ten or more), methods for exploring the space (Markov-Chain Monte Carlo) or integrating over it (nested sampling) need to be applied in order to achieve accurate results in a sensible amount of computer time. There is a lot of useful discussion on these issues and their applications, although one might wonder if a huge amount of value is added by having these articles in a single book, given that good reviews of these topics by the same authors have been published elsewhere and are freely available on the internet. But for students and others with little prior exposure to the subject, this collection should have a valuable function in raising awareness of these techniques.

One final thought about the book is that it might have benefitted from including more sceptical voices. I gave a talk at the 2006 meeting, which tried to highlight some of the reasons why the Bayesian approach continues to be controversial. This comes down to the arbitrary nature of the priors that need to be assumed to make the methods work; a prior is often chosen with rather little justification, and the probabilities that arise from using it are used to make binary decisions (accept or reject a theory) without acknowledging that the Bayesian probability was not a very well-specified number in the first place. I can understand why such views were not thought suitable for inclusion in a volume that is trying to 'sell' the positive aspects of Bayesian methods, but I was pleased to see something of the same flavour emerging in Mortlock's article on flux measurement. Here, the Bayesian method requires the number counts of the population being studied — but this amounts to knowing the result of flux measurements before you start. The standard answer is that good data will overwhelm a poor choice of prior, and this is true; but advanced statistical methods tend to be used most where the data are perhaps just sufficient to reach a conclusion, so this freedom in prior choice remains an issue for practical applications. More open discussion of this point might have given helpful guidance to the new Bayesians that this book will doubtless help to create. — JOHN PEACOCK.

The Cosmic Microwave Background: From Quantum Fluctuations to the Present Universe, edited by J. A. Rubiño-Martin, R. Rebolo & E. Mediavilla (Cambridge University Press), 2009. Pp. 304, 25·5 × 18 cm. Price £75/$120 (hardbound; ISBN 978 0 521 76453 7).

Over the past decade, cosmic microwave background (CMB) data have provided high-precision measurements of the contents and history of our Universe. The leap in data quality promised by the *Planck* satellite, currently mapping the microwave sky, means that we may expect some new revelations in the next few years, especially about the physics of the early Universe. Thus, this volume, which presents the lectures of the nineteenth Canary Islands Winter School on the subject of the CMB, seems particularly timely.

The individual chapters, written by leading researchers in the field, cover a wide range of topics, from experimental design, the physics of the early Universe and the CMB, the properties of CMB foregrounds, and a very readable review-style final chapter covering many aspects of observational cosmology not specific to the CMB field. I was especially pleased to find a chapter on statistical techniques for cosmological-data analysis, covering tools and techniques in which students often do not receive formal training, yet are essential for successful research in cosmology.

In many chapters there is an emphasis on the most recent results and currently-favoured models. While only time will tell if some of these results pass the test of next-generation experimental data, this makes the volume a good crash course for a research student attempting to get up-to-date information. Indeed, this is a particular attraction of the book: much of the information can be found in other sources, but rarely is it collated together this coherently in a single place. There is a good balance between reviewing recent results and more pedagogical material. While the 'voice' varies between chapters, understandable given that they were written by different individuals, many authors use an informal style which makes for engaging reading.

This volume would make highly recommended reading for research students in cosmology, and would not look amiss on the bookshelf of the seasoned researcher as a handy reference. Due to the advanced level of the material, I would not recommend it for anyone who has not taken a high-level cosmology course. — HIRANYA PEIRIS.

Structures in the Universe by Exact Methods: Formation, Evolution, Interactions, by K. Bolejko, A. Krasiński, C. Hellaby & M.-N. Célérier (Cambridge University Press), 2009, Pp. 242, 25·5 × 18 cm. Price £75/$120 (hardbound; ISBN 978 0 521 76914 3).

The book does exactly what it says in its title: studies some fundamental aspects of cosmology using exact (analytical) methods focussing on the use of Lemaître–Tolman (L–T) models. It covers a wide range of recent developments in the area, and fills a gap in the current literature. Despite its analytical approach, it keeps a very good connection with observations.

The volume takes the form of a collection of research papers on the subject, a fact that makes it a rather advanced book, yet it remains clear and well presented. It requires that the reader has a background in both General Relativity and cosmology/astrophysics, in particular research areas of the CMB, structure formation, black holes, late-time acceleration, and the cosmological-constant problem. It is aimed at advanced research students and experienced researchers, and covers a very wide area of both theory and applications of (but not only) L–T models, being at the same time quite clear and explicit, presenting the intermediate calculations and solutions. In this way it provides a powerful tool for potential researchers in the area.

The book is divided into two main sections, firstly giving the theoretical background and then moving on to the applications to cosmology. In the first part, the main concepts and mathematical methods needed to understand and apply L–T models are introduced thoroughly. The second part discusses the application of L–T models in cosmology, discussing, for example, the way L–T models can overcome the cosmological-constant problem, or explain the CMB anisotropies. Furthermore, constraints on L–T models coming from observations, such as measurements of type-Ia supernovae or baryon acoustic oscillations, are also discussed.

To sum up, it is definitely a book that everyone who wishes to do research in the area of non-homogeneous cosmology should have. — IPPOCRATIS SALTAS.

THESIS ABSTRACTS

A SPECTROSCOPIC STUDY OF THE RAPIDLY OSCILLATING PECULIAR (A) STAR HD 134214

By Jonathan D. Riley

Photometric studies were made of ten peculiar-A-type (Ap) stars in a search for long-period oscillations typical of rapidly-oscillating Ap stars (roAp stars) with the 0·75-m telescope at the South African Astronomical Observatory. Although a promising candidate pulsator was found in HD 156869, no such oscillations were seen in those ten stars. Further spectroscopic observations did discover a 21-minute pulsation in HD 116114, and as a result further investigations were confined to spectroscopy.

In addition, a theoretical model of the atmosphere of an roAp star was developed involving a standing wave with a running-wave component. This model appears to be more consistent with previous results from roAp stars and also with the results presented in this thesis, in terms of pulsation phase and amplitude behaviour.

Using high-resolution *VLT*/*UVES* spectroscopic data, an abundance analysis has been performed for the rapidly oscillating Ap star HD 134214, the shortest-period roAp star known. An atmosphere with $T_{\rm eff} = 7800$ K and log $g = 4{\cdot}2$ and calculated with the package ATLAS9 was found to fit the data best, with a microturbulence of 0·5 km s^{-1}. It was possible to identify 139 good-quality Fe I lines and 38 Fe II lines of similar quality, so the above atmospheric parameters could be calculated with a high level of confidence. The problems in determining these parameters are discussed in detail, along with the limitations of previous work.

The abundance analysis was performed with the programs WIDTH9 to calculate abundances from measured equivalent widths and SYNTH in order to fit calculated profiles. There were 610 lines identified, which had abundances calculated, covering 46 different ion species.

The abundance pattern found is similar to that seen in other Ap stars, with the Fe-peak elements being, in general, either of solar abundance or slightly overabundant. The rare-earth elements are very overabundant compared with the solar values and an abundance anomaly of 1·2 and 1·4 dex is seen between the first and second ions of Pr and Nd. This is similar to that seen in other Ap stars and is suggestive that these elements may be stratified in the atmosphere of HD 134214 and other Ap stars.

The lines used in the abundance analysis were then investigated for evidence of pulsations. As is typical for the Ap stars, the rare-earth elements showed the strongest pulsations. Most of the lines show phases that are concentrated within the range –0·5 to 0·5, but Pr III, Tb III, and Th III show significant deviations from this value. The lines of La II and Nd III show evidence of a running wave in the atmosphere, and it is postulated that these lines are probing regions close to nodes of the pulsation, where the amplitude becomes low and the running component of the wave begins to dominate, causing the phase to run away. It is tentatively suggested that Nd II may be situated at an antinode, with La II and Nd III probing the nodes on either side.

Despite the analyses that have been performed, it is not clear what marks HD 134214 as different from other roAp stars and causes it to show such a short pulsation period. Both the abundance patterns and pulsational behaviour of the star in every other way seem to be typical of many other roAp stars. — *University of Central Lancashire; accepted 2009 June*.

Galaxies in the Distant Universe: Colours, Redshifts, and Star Formation

By Manda Banerji

This thesis explores the properties of distant galaxies in the Universe, in particular their redshifts, morphologies, evolutionary history, and star-formation processes within them.

The first part is concerned with photometric-redshift estimation. I present different photo-z methods and compare them using a sample of luminous red galaxies (LRGs). Photo-z design studies are then carried out for the upcoming Dark Energy Survey as well as the planned space-based *Euclid* mission. I show the importance of adding near-infrared data to optical data in obtaining accurate redshift estimates for both these projects, and how this may prove crucial for some of the cosmological analyses intended with them.

In Chapter 5, I present automated morphological classifications for about 1 million objects from the Sloan Digital Sky Survey and compare them to visual classifications of the same objects obtained as part of the Galaxy Zoo project. I find that a neural network is able to reproduce the human classifications to an accuracy of better than 90%.

In Chapter 6, I study the evolution of the luminosity and mass functions of LRGs by using spectroscopic data. I find that these objects are mainly composed of old stars that were formed very early in the history of the Universe and also that the most massive objects were already well assembled at redshifts of ~0·8, in direct contradiction to predictions of most current models of galaxy formation.

Chapter 7 presents an alternative means of determining the approximate nature of the stellar initial mass function (IMF) of extragalactic systems by considering time-scales for low-mass-star formation in different environments. I find that a galaxy's metallicity is a key parameter in determining the shape of its IMF and make some predictions about trends in molecular emission in different extragalactic systems with different IMFs. — *University College London; accepted 2009 August*.

An Optical and Infrared Analysis of Blue Compact Galaxies

By Bethan James

An understanding of blue compact dwarf galaxies (BCDs) and the processes occurring within their chemically un-evolved environments is fundamental in our understanding of the early Universe. This thesis presents an investigation into their physical conditions, kinematics, chemical abundances, and dust compositions.

An optical integral-field-spectroscopy investigation of two perturbed BCDs, UM420 and UM462, is presented. Emission-line maps show that both galaxies display signs of on-going perturbation and/or interaction. Electron temperatures, densities, and chemical abundances are computed from spectra integrated over the whole galaxies and for each area of star formation.

A similar yet more complicated analysis is undertaken of the BCD Mrk 996, which displays multi-component emission lines. The high-excitation-energy [O III] λ4363 and [N II] λ5755 lines are detected only in the inner regions and purely in broad-component form, implying unusual excitation conditions. A separate physical analysis of the broad- and narrow-emission-line regions is undertaken, yielding a revised metallicity and N/O ratio typical for the galaxy's metallicity.

The mid-IR properties of 19 BCDs are studied through *Spitzer* spectral and imaging data. The depletion of PAH emission in BCDs is investigated and found to be due to formation and destruction effects. The [Si III] flux ratio is used as a density diagnostic, showing typically low densities. Maps of PAH emission and radiation-field hardness are derived from IRS spectral-mapping data. Blackbody fits to IR photometric SEDs typically reveal two dust components.

The observed physical and chemical properties of Mrk 996 are successfully reproduced with the photoionization code MOCASSIN. The best-fit model involved the inclusion of a filling factor and an amorphous carbon-dust component with a two-zone dust distribution. A STARBURST99 input spectrum was used, yielding ages consistent with the known young WR stars and old super star clusters within Mrk 996. — *University College London; accepted 2009 October*.

OBITUARIES

Douglas Walter Noble Stibbs (*1919–2010*)

With the death on 2010 April 12 of Professor Walter Stibbs, astronomy has lost one of its more colourful characters and a true servant of our discipline for over 70 years. Born in Sydney on 1919 February 17 of Scottish ancestry, he was educated locally and entered his home town university in 1937, to emerge with a first-class honours BSc in 1942, the seemingly long duration of the course being explained by war-related work as a research assistant at the Commonwealth Solar Observatory (CSO) (1940–1942). An MSc followed in 1943 by which time he was already an assistant lecturer at Sydney University.

Having previously met Richard van der Riet Woolley at CSO when he arrived as a Vacation Student in 1939 December, Stibbs returned to the CSO at Mt. Stromlo in 1945. This was the start of a long association with Woolley, the principal legacy of which is the important textbook on radiative transfer, *The Outer Layers of a Star* (Clarendon Press, Oxford, 1953). At that time, and on the basis of photometry from Mt. Stromlo, he also developed the idea of the oblique-rotator model to explain the spectroscopic behaviour of the magnetic star HD 125248 (*MNRAS*, **110**, 395, 1950), one that subsequently found wide application in the study of Ap stars. Moving on to Oxford in 1950 as a Radcliffe Travelling Fellow, Stibbs carried out observations in Pretoria on the topic of Galactic rotation, with an important contribution on the kinematics of Cepheid variables (see *MNRAS*, **116**, 453, 1956). That gained him his DPhil and the Johnson Memorial Prize. The next move, in 1955, was to the UKAEA at Aldermaston, where his expertise in radiative transfer was put to good use in the study of neutron diffusion in nuclear reactors.

In 1959, Stibbs succeeded Erwin Finlay-Freundlich to become the Napier Professor of Astronomy at the University of St. Andrews, and it was in that capacity that he will be remembered by many in the astronomical community. He trebled the size of the department and installed what was at the time (and again now is) the largest telescope in the UK: the 37-inch *James Gregory Telescope*. And it was in 1964, as an undergraduate at one of just four UK universities that offered an astronomy course in those days, that I first encountered 'the Prof.' The Department of Astronomy was still based out at the observatory on the edge of the playing fields and thus had that rather special atmosphere that observatories used to have (and which is now completely lost in the merger with the physics department in office blocks in the town). Stibbs, always immaculately attired in three-piece suit and academic gown, lectured to the honours classes on stellar kinematics and on radiative transfer (including the greenhouse effect in planetary atmospheres (*ApJ*, **168**, 155, 1971) — way before the current enthusiasm for the subject), and could hold me spellbound for an hour and a half or more. He ran the observatory effectively by way of a series of Observatory Staff Notices (OSNs) which made very clear the way things were to be done; indeed, so memorable were those OSNs that they have been collected into two volumes for the enjoyment of past students. While at St. Andrews, Stibbs held a number of important posts including those with the IAU, the RAS, and the Science Research Council and its various committees, and thus contributed to the running of astronomy both nationally and internationally.

On retirement from St. Andrews, Stibbs returned to Australia where he continued to play an active rôle, giving courses at the Mt. Stromlo and Siding Spring Observatories and at the Astrophysical Theory Centre at the ANU.

Stibbs had other talents besides his scientific ones: he was an enthusiastic marathon runner, a photographer, an expert organist with a deep knowledge of French music for that instrument, and a dab hand at cricket. Indeed, he was the star of a match played at Herstmonceux on the occasion of the tercentenary celebrations, between Sir Richard Woolley's team and a 'Rest of the World' eleven. (But it was rumoured that he'd been coached at university by Sir Don Bradman, so perhaps his success was not surprising.)

Walter Stibbs is survived by his wife Margaret, whom he married in 1949, and daughter Helen. — DAVID STICKLAND.

Sidney Charles Bartholomew 'Ben' Gascoigne (*1915–2010*)

Many visitors to the 3·9-metre *Anglo-Australian Telescope* (*AAT*) are surprised to see a rather elegant plaque, fixed to the inner walkway of the dome at a point where it soars some six metres above the observing floor below. It is engraved 'Gascoigne's Leap' — and if you think this is starting to sound ominous, you're right. Back in 1974 April, when the telescope was brand new, Professor Ben Gascoigne was the senior commissioning astronomer. One observing night, he had to pop outside to check if there was cloud around. Coming back in from the high outer walkway in pitch darkness, he headed the wrong way, and stepped not into the control-room, but into thin air. He was very lucky. He missed protruding steel supports by inches, and suffered only a broken elbow. As luck would have it, he also missed the steelwork of a safety rail, designed to prevent just such an accident, which was waiting on the dome floor to be installed. Needless to say, fitting it was the number one priority the next day, and safety in this hazardous building was never again taken for granted.

You could say that Ben Gascoigne epitomised the resourceful, resilient, innovative — and fairly unbreakable — *AAT* astronomer, even though the institution he belonged to for most of his long career was actually the Australian National University (ANU). Ben brought to his work a broad range of skills, contributing significantly to our understanding of the evolution of stars and the cosmic distance scale. Moreover, while he was neither Anglo nor Australian, hailing from New Zealand, he always embraced the community of British and Australian astronomers with warmth and generosity. With Ben's passing in Canberra on March 25, Australasian science has lost one of its best-loved practitioners.

Ben Gascoigne was born in the art-deco town of Napier on 1915 November 11. The eldest of four children, he was the family's golden boy, excelling in his studies at Auckland Boys' Grammar School and facing his university entrance year in 1933 with only one dilemma troubling him — whether to study history, or maths and science. The graceful ease with which Ben moved between the arts and the sciences was clearly present at an early age. His response to the problem was typically pragmatic. He had grown up with a severe stammer, and reckoned that it would be less of a hindrance in a scientific job than in a career in the humanities — thus, science it was. The eventual outcome of that decision was what would today be called a 'double-first' in mathematics and physics, awarded by Auckland University College of the University of New Zealand. This provided Ben with a scholarship to the University of Bristol, from where he graduated with a PhD in physics — specifically optical science — in 1942.

By that time, Ben had already returned to the southern hemisphere, taking the last available boat from embattled Britain in 1940 July. He was anxious not to miss an Auckland girl called Rosalie Walker, about whom he had "long since made up his mind". They were married in 1943, by which time Ben was immersed in the design of gun-sights at Mount Stromlo Observatory in Canberra (later to become part of the ANU). That led to his first astronomical job, the setting-up of the Commonwealth Time Service in 1944. With the end of hostilities, Ben's fluency in both optics and astronomy led him easily into the fundamental research that became the hallmark of his career. Working amongst some of the greatest names in astronomy of the day — Woolley, Allen, de Vaucouleurs, Bok — Ben made many significant discoveries, most notably that the distances to the Magellanic Clouds had been underestimated by a significant factor. This, in turn, revised our understanding of the distance scale of the Universe, and consequently its age.

Clever use of optical instruments was a continuing theme and when, in 1967 April, the British and Australian Governments decided to proceed with the building of a 4-metre-class telescope, Ben was appointed to a select technical committee, eventually becoming joint Project Scientist with R. O. Redman of Cambridge University. It was a job of which Ben said, "I felt almost as if I had been preparing for it all my life", and, indeed, it is difficult to overstate his contribution to the planning, construction, and commissioning of the *AAT*.

At the close of Ben's association with the fledgling *AAT* in 1975, he was offered a senior appointment on the AAO's staff in Sydney. He had good reason to accept — he knew that his return to Mount Stromlo would be soured by his unaccountably poor standing in the eyes of its then-Director, Olin Eggen. But he declined the offer in order to remain in Canberra where Rosalie was on the brink of a remarkable career as one of Australia's greatest contemporary artists.

By the time Ben retired formally from Mount Stromlo in 1980 amidst accolades and honours, his own career had come full-circle. In his spare time, he pursued both astronomical research and his beloved history. But his day-job was even closer to his heart. He was Rosalie's right-hand man, supporting her work, and archiving and photographing all her magnificent creations. He was also the consummate family man — father (to Martin, Toss, and Hester) and grandfather. — FRED WATSON.

John Griffiths (*1952–2010*)

I first met John Griffiths in 1970 when we both arrived at University College London as undergraduates to read astronomy. Our class of 23 students was the first 'big year' in the Astronomy Department headed by its first Perren Professor, C. W. Allen. John's enthusiasm for astronomy inspired us all and we have remained friends ever since. For his final-year research project he undertook a detailed study of the variable Be star γ Cassiopeiae, using photographic prismatic spectra obtained during WWII by Margaret Burbidge with the 24-inch telescope at Mill Hill. John graduated with a 1st-Class Honours BSc in Astronomy in 1973, under the 2nd Perren Professor, Sir Robert Wilson. He stayed on at UCL to undertake a PhD in the newly formed ground-based-infrared-astronomy group, supervised by its leader Dr. David Aitken. Using a novel near-to-mid-IR spectrograph, he conducted pioneering IR spectroscopy of Galactic H II regions and the Galactic Centre with the *INT* at Herstmonceux, the 60-inch on Tenerife, and the *AAT*. This work included high-resolution source mapping in the IR continuum and the Ne II 12·8-μm fine-structure line. For the Galactic Centre he showed that the Ne II data implied a heavy-element overabundance of a factor of 3 compared to solar values, with ionization provided by stars with effective temperatures of around 40 000 K. He gained his PhD in 1977 on 'The Galactic H II region G333·6–0·2', showing that the dust heating in the region arises from the absorption of Ly-α radiation, with the dust-to-gas ratio depleted by a factor of 100 in the core. This work led to several publications in *MNRAS*, and John was soon elected a Fellow of the RAS.

John left UCL and, after a three-year period teaching physics in secondary schools in London, embarked on the career for which he will be best remembered — teaching astronomy to the general public. John had the remarkable gift of not only knowing his subject backwards, but being able to get it across with clarity and inspiration to people of all ages and aptitudes. From 1981 to 2002 he had a glittering career at the Science Museum in London (part of NMSI), developing several inspirational exhibitions, including topics on astronomy, space science, rocketry, lasers, and holograms. His book, *Lasers and Holograms*, was published in 1982 and reprinted in 1986. He also produced four chapters for the encyclopaedia *Space Astronomy and Robot Explorers*, in 1984. John took early retirement from the NMSI and became a free-lance astronomy educator, giving talks to numerous schools, astronomical societies, and at the Herstmonceux science centre. He initiated and taught astronomy classes at adult-education colleges in London, where he also taught GCSE astronomy for gifted children and set up and ran astronomy summer-schools for Greenwich Council. He initiated an amateur astronomy group in Grove Park, where he lived, and had long-standing associations with the Flamsteed and Herschel Societies and the BAA. He was also snapped up by the Royal Observatory Greenwich to teach GCSE astronomy there and run planetarium sessions at the National Maritime Museum for schools and the public, including 'Evenings with the Stars' sessions on the 28-inch refracting telescope at the ROG. The huge number of people he has taught, from the very young to the very old, have benefitted greatly from his knowledge and been inspired by his boundless and infectious enthusiasm for astronomy — a fitting legacy.

In 2003 John and his wife Kath bought a second home in Andalucia, Spain, just outside the village of El Bosque in the foothills of the Grazalema National Park. Their house, built into the side of a cliff, with its terraced garden, afforded wonderful clear views of the night sky, and in keeping with his passion for astronomy, John built an observatory there, with a computer-controlled 14-inch telescope and seven smaller instruments. Together with a colleague, Andy Burns, John further developed the observatory and entered into an arrangement with Glamorgan University to allow their students to use this observatory for field trips. The inaugural group had just completed their first visit when tragedy struck on 2010 April 9 and John unexpectedly died of a heart attack. I understand that his wife intends to maintain the house and observatory in El Bosque for use by university students, schools, and individuals, and this will be a fitting testament to John.

John Griffiths was born on 1952 June 15 in the village of Ystradgynlais in Wales, and completed his secondary education at Maesydderwen Comprehensive School. He had a passion for all things Welsh, not least their national rugby side. He was a qualified soccer and rugby referee and a keen cricketer. John is survived by his beloved wife Kath, whom he married in 1973, his mother Dorothy, and sister Ann. His funeral near Ystradgynlais was attended by numerous friends from his schooldays, fellow astronomy undergraduates from his UCL time, colleagues from the Science Museum, the Royal Observatory Greenwich, and friends from throughout the country and abroad. Those who have had the privilege to know John will always remember him with affection and gratitude for his friendship and his manifest contribution to the public understanding of science and of astronomy in particular. — ALLAN WILLIS.

Here and There

BUT MAYBE NOT VERY ACCURATE?

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