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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2011 January 14 at $16^h 00^m$
in the Geological Society Lecture Theatre, Burlington House

R. L. DAVIES, *President*
in the Chair

The President. Good afternoon; I wish you all a very happy New Year!

It's one of my pleasures in the Presidential rôle to announce the recipients of the Society's awards for 2011. The Gold Medals of this Society are awarded to Professor Richard Ellis at Caltech, and Professor Eberhard Grün at Heidelberg. The Eddington Medal is awarded to Professor Gilles Chabrier from Lyon and Exeter, the Price Medal to Professor Roger Searle from Durham, the Jackson-Gwilt Medal to Professor Matt Griffin from Cardiff, and the Fowler Awards to Dr. Vasily Belokurov from Cambridge and Dr. James Wookey from Bristol. The Winton Capital Awards go to Dr. Sugata Kaviraj at Imperial College and Oxford, and Dr. Leigh Fletcher from Oxford. We have elected honorary Fellows — Professor Beatriz Barbuy from Sao Paolo, Brazil, Dr. Christine Jones from the Center for Astrophysics in Harvard, Professor Jan Palouš from Prague, Professor Siegfried Bauer from Graz, Professor Margaret Kivelson from Los Angeles, and Professor Saku Tsuneta from Tokyo. The Harold Jeffreys Lecturer for 2011 is Dr. Lyndsay Fletcher from Glasgow, the Darwin Lecturer is Professor Michael Turner from Chicago, and the Gerald Whitrow Lecturer is Professor Alex Vilenkin from Tufts University in Boston. Let's congratulate all of our awardees! [Applause.]

And before we hear from the winners of the best theses submitted in 2009, it is my privilege to be able to present them with their cheques: the first is Dr. Baojiu Li, from the Department of Applied Mathematics and Theoretical Physics in Cambridge; and Dr. David Halliday, whose PhD is from Edinburgh but who is now at the Schlumberger Research Centre in Cambridge. Congratulations! [Applause.]

We move on to the main part of the programme, and the first speaker is Göran Pilbratt, from ESA, on '*Herschel*: the cool Universe gets cooler'.

Dr. G. L. Pilbratt. The *Herschel Space Observatory* was successfully launched on 2009 May 14, carried into space by an Ariane 5 ECA launcher together with the second passenger *Planck*, both spacecraft being injected into transfer trajectories towards their operational orbits around L2 with exquisite precision.

Herschel (Pilbratt *et al.*, *A&A*, **518**, L1, 2010) is the latest observatory mission in the European Space Agency (ESA) science programme. It carries a 3·5-metre-diameter passively-cooled silicon-carbide Cassegrain telescope. The focal-plane units of the three science instruments, the *Photodetector Array Camera and Spectrometer* (*PACS*), the *Spectral and Photometric Imaging REceiver* (*SPIRE*), and the very-high-resolution *Heterodyne Instrument for the Far-Infrared* (*HIFI*) spectrometer, are housed in a superfluid-helium cryostat which is providing the necessary thermal environment as well as determining the ultimate lifetime of the Observatory.

Herschel has been designed to build on previous observing capabilities by providing the first large-aperture space infrared observatory, and by extending the wavelength coverage into the submillimetre. In addition, *Herschel* for the first time is providing a very-high-spectral-resolution (heterodyne) capability over a wide spectral range. Thanks to its large telescope and complement of three novel science instruments it offers unprecedented observational capabilities in the spectral range 55–671 μm. Infrared-dominated galaxies at look-back times up to 10–12 Gyr and protostars in our Galaxy have spectral-energy distributions that peak in the *Herschel* spectral range, but *Herschel*, being an observatory, is not limited to any particular targets but responds to proposals from its observer community.

I would like to demonstrate some of the scientific results from *Herschel* by presenting a few selected highlights; many of these are reported in a special issue of *Astronomy & Astrophysics* (volume **518**, 2010). Looking at star formation within our own Galaxy, a composite *PACS*/*SPIRE* image of a stellar nursery in Aquila shows filaments containing several hundred compact starless cores, many of which are gravitationally bound, and about 200 protostars. From these images, one can extract the core mass function, which is found to have exactly the same shape as the stellar initial mass function; one can interpret the difference in position of the curves as some kind of measure of star-formation efficiency. But the authors of this work have also identified the physical properties of filaments which contain pre-stellar cores likely to go on to form stars; there is a critical mass per unit length for the filaments to be able to form stars.

The richness of results which can be obtained with *HIFI* is illustrated by the most complete high-quality IR spectrum of the Orion Nebula ever obtained: the entire spectrum from 500–1900 GHz has been recorded, in which about 100 000 emission lines are detected; many important molecular species can be identified, including water and organic molecules, and work is on-going to identify many other emission lines.

Herschel is well suited to the detection of dusty rings around stars, such as the one seen around HD 207129. The existence of dust particles in systems such as this one implies a population of planetesimals which are ground down through collisions to replenish the disc. In this case, the temperature of the dust can be inferred, but it is very difficult to fit the dust-grain properties to form a credible model.

Herschel has also been used to observe circumstellar material which is being shed in the late stages of stellar evolution: the circumstellar material around α Ori shows an impressive series of shock waves as the star moves through the ISM, and detailed modelling of these structures is in progress. *Herschel* spectra of evolved stars are helping us to understand their evolution and environments. About ten years ago, just one water line was detected around the carbon-rich star IRC +10° 216 — since all oxygen is expected to be locked up in CO in outflows from such sources, the explanation given at the time to explain the presence of an O-bearing molecule like water was that comets might be evaporating around the star. *Herschel* has now detected over 60 water lines, but since some imply an excitation temperature of about 1000 K, that is quite incompatible with the cometary model. In a revised model based on *Herschel* data, the stellar UV field frees oxygen atoms from species such as ^{13}CO and SiO, and the oxygen then reacts with hydrogen to form water — but this model also requires the circumstellar material to be very clumpy.

The impact of *Herschel* on extragalactic studies can be demonstrated with a *SPIRE* three-colour image of the Great Observatories Origins Deep Survey – North containing thousands of visible galaxies; the famous *JCMT SCUBA* image of the same field was obtained in 20 nights, and found to contain five sources. This illustrates the progress that an IR space observatory offers: the field was observed by *Herschel* in 16 hours of integration to a depth which reveals 7000 sources. Within a subset of these for which redshifts are known, one can see evidence for significant galaxy evolution over the most recent couple of billion years.

In all these studies, and more, *Herschel* has provided the data which are enabling us to take the next step in our understanding of the formation and evolution of stars and galaxies. The first year in flight for *Herschel* has been incredibly intensive, and the reward is a performance beyond expectations in most respects. *Herschel* is undoubtedly a great success and the observational results show that it will have a fundamental impact on research in many areas of astronomy. With *Herschel* we are literally already seeing what nobody has seen before, and this is but the beginning!

Information and images relating to *Herschel* science can be accessed from http://sci.esa.int/herschel.

The President. Thank you, that's terrific and it's wonderful to see. Any questions?

Mr. D. Lally. The mission time is 3–3·5 years; if it goes beyond its design lifetime, it's still going to be very valuable.

Dr. Pilbratt. *Herschel* is going to be extremely valuable until it runs out of helium, and that is a predictable situation. It is difficult to predict with very high precision, but *Herschel* will run out of helium most likely sometime around 2012 November. With a bit of luck we will have *Herschel* for another two years.

Mr. M. F. Osmaston. What was the source for your spectrum with 100 000 lines? And have you weeded out the Doppler effect which produces shifts of the same; or are they actual distinct spectral lines?

Dr. Pilbratt. They are distinct spectral lines, but of course many of them come from the same species. The source that was observed is the Kleinmann–Low nebula, in Orion, an area of star formation. We correct for the radial velocities at the source, and the velocities within the source are very small in comparison with the bandwidths that we have.

The President. Have you discovered lines that have not been seen before in the lab?

Dr. Pilbratt. We have unidentified lines, yes, so lots of work to do.

The President. I think we should thank you again. [Applause.] The next talk is by Allan Chapman from Wadham College in Oxford, on Mary Somerville.

Dr. A. Chapman. Along with Caroline Herschel, Mary Somerville was one of the two women honoured by the Royal Astronomical Society in 1835. For though women would not be admitted to the full Fellowship on equal terms with men until 1916, the established astronomical distinction of Miss Herschel and Mrs Somerville led to their being made Honorary Members of the Society.

Mary Fairfax, as she was before marriage, was a Scot, born at The Manse, Jedburgh, in 1780, the daughter of Royal Navy Captain, later Admiral, Sir William Fairfax, and with a battery of relations who were lawyers, Ministers of the Kirk, Edinburgh professionals, and military officers. Perhaps because her father was a prisoner of war during her earliest years — she did not recognize him when he came home — her early education was erratic. Allowed to run wild around the Firth of Forth, she grew up to have an iron constitution, an intellectual curiosity then thought odd in young ladies, natural social skills, and a fine sense of humour, combined with natural elegance and very good looks. An army-officer uncle, on leave from India, took upon himself what turned out to be the very easy task of teaching his little niece how to swear like a British trooper! On being asked one day by a lady, when walking around Edinburgh with her maid, what was the name of the pretty child, Mary replied "What's your business, you damned B —?" [probably 'Bugger', a favourite armed-forces word in the 18th Century].

What makes this incident significant is the fact that, 75 or so years later, when she was writing her *Reminiscences*, Mary still had the sense of mischief to relish recording it in detail. Sadly, it was expunged from the published *Reminiscences* edited by her daughters, Martha and Mary, in 1873, who clearly did not regard such behaviour as compatible with that of a Victorian female icon. Yet it is in her original manuscript in the Bodleian Library, Oxford, and both Dorothy McMillan and I restored it in our respective *Queen of Science. Personal Recollections of Mary Somerville* (Canongate Classics, 102, Edinburgh, 2001), p. 9, a new scholarly edition of the original *Reminiscences*, and *Mary Somerville and the World of Science* (Canopus, Bristol, 2004), p. 23.

Mary discovered her passion for mathematics and astronomy some years later when, reading a women's magazine, she asked her friend Miss Ogilvie what some symbols in a puzzle meant, only to be told they were "a Kind of Arithmetic: they call it Algebra". She was hooked. Looking at her elder student brother's and father's books, she began her mathematical odyssey, in the teeth of her parents' opposition. For mathematics could seriously damage a girl's brain, they believed! She persisted, however, and struck a deal with them that she would be allowed a limited amount of mathematical reading each day, as she became enthralled by the strange power of numbers, mathematical concepts, planetary orbits, and astronomy. The astronomy which most captured her imagination, however, was not the viewing of the Moon and planets through a telescope, but the abstruse delights of gravitational physics and cosmology.

It was following the death of her first husband Captain Samuel Greig in 1807, after only three years of marriage, that Mary's real scientific career began. The raising of a family, the social duties of a naval officer's wife, and Captain Greig's low opinion of the intellectual capacities of women had put her studies on hold, but as a suddenly independent young widow, she moved back to her old family home, at Burntisland, near Edinburgh, and began to receive private tutorials in higher mathematics from Dr. William Wallace, who in 1819 would become Professor of Mathematics at the University. In the early 19th Century, British mathematics — perhaps because of its reverence for Newton — lagged well behind that of France, and it was Wallace who encouraged Mary to buy and study copies of Lagrange, La Croix, and especially Laplace. For while Great Britain was locked in a European struggle against Bonaparte's military dictatorship, French and British *savants* continued to enjoy friendly relations, and their books were available in one another's countries. And quite simply, Mary took to the most sophisticated mathematical astronomy like a duck to water.

Then in 1812, she married her older cousin, Dr. William Somerville, MD, a senior British Army medical officer. Unlike her first husband, Greig, Somerville admired his wife's intellect and did all in his power to encourage her. An FRS in his own right, and soon to become Physician to the Chelsea Hospital — one of the top jobs in the Army Medical Department — William's career in medicine was in no way in conflict with Mary's in mathematical astronomy. Relocated in London, Mary enjoyed the social life. For though an increasingly prominent female intellectual, she was always proudly feminine, loving parties, theatre, balls, and fashions, and making it clear to all that she was most definitely not a 'blue stocking'. Through the Royal Society, Royal Institution, and other bodies, Mary came into creative social contact with the Herschels (she and Sir John became lifelong friends and correspondents), Davy, Faraday, and Whewell; it was Sir James South who would become the first, as Charter President of the RAS, 1829–31, to give Mary lessons in practical, instrumental mathematical astronomy at his superbly-equipped private observatory at Campden Hill, West London.

When the Somervilles made their first visit to the European Continent in 1817, two years after the Battle of Waterloo had brought peace to Europe, Mary found that she was already famous there, as the French *savants* queued up to meet the British female mathematician. Staying with the Aragos at the Paris Observatory, Mary and William received a guided tour of the French National Observatory from the Director, François Arago. Indeed, the whole of Parisian science, the most eminent of whom was the elderly Pierre Simon Laplace, whose monumental *Mécanique Céleste* (1799–1825) had transformed mathematical astronomy, wanted to meet Mary. And after leaving Paris, the Somervilles were to travel on *via* Geneva to Italy, where Mary, in spite of being a staunch Scottish Protestant, had an audience with Pope Pius VII, whom she described as "a handsome, gentlemanly and amiable old man".

Yet in 1817, Mary Somerville had published nothing, so how could she have been so famous? Of course, the scientific and cultural worlds were much smaller in 1817 than they are today, and reputations were often carried by letter and by word of mouth. That, I think, is how her early reputation spread so rapidly and so far, for then, as now, science was an international pursuit. Indeed, not until 1825–6 did she publish any of her researches, when, in *Philosophical Transactions*, she described her efforts to test Professor Morichini's experiment to magnetize slivers of metal by exposing them to the violet rays of the solar spectrum.

Mary's first book, *Mechanism of the Heavens* (1831), was a study initially suggested by the Somervilles' Edinburgh lawyer friend Lord Henry Brougham, who was himself fascinated by science. Brougham had suggested that Mary might write an accessible digest of Laplace's multi-volume and formidable *Mécanique* in 1826, but once the bit was between her teeth, then things took off. Instead of a digest, the *Mechanism* developed into an original, sustained, analytical essay on Laplacian celestial mechanics and gravitation theory, of which non-mathematicians can scarcely advance beyond the Introduction! It caused a sensation in 1831, not only because of its mathematical and imaginative brilliance, but also because it was the work of a woman. Moreover, it became the first work by a female author to be employed in the teaching of the Mathematical Tripos at Cambridge, when the Somervilles' friend William Whewell began to use it as a textbook for the Trinity College mathematicians.

Mary's publisher then approached her for another more-accessible equation-free book, which came out as *On the Connexion of the Physical Sciences* (1834), and was a masterpiece by any standards. For that work took on no less than the intellectual and mathematical unity of all the known physical sciences, examining the whole of gravitation theory, magnetism, electricity, optics, and cosmology. And as with her *Mechanism*, her friend Sir John Herschel acted as manuscript reader, critic, and commentator, and their letters are preserved in the Herschel correspondence in the Royal Society Library.

In 1840, the 69-year-old Dr. Somerville retired from Chelsea Hospital, and partly because of his own deteriorating health (though he would live to 86) and partly because of financial losses incurred in the merry-go-round of late Georgian finance, the couple left England to live in Italy, where the climate was milder and the cost of living much lower. They would both die in Italy, in 1857 and 1872 respectively, and be buried in the English Cemetery in Naples.

In Italy, Mary continued to read, correspond, and think as actively as ever, and as her books had sold well (especially the *Connexion*), she planned a new major work, *Physical Geography* (1848). Like her two previous books, this great work of synthesis demonstrated a remarkable range of knowledge, but linking all together in physics. She examined the effects of gravitation on the shape and continents of the globe, and looked at mountain-building, vulcanism, and earthquakes. Geology, let us not forget, was advancing rapidly, and the Somervilles were on close personal terms with geologists of the eminence of Canon William Buckland and Sir Roderick Murchison. Then her interest in the newly-discovered 'invisible', or ultraviolet, rays of the Sun and their rôle in the development of all organic life led her to examine the relationship between optics and flora and fauna distribution across the planet — a pioneering major study, indeed, in what we would now call environmental science and climatology, standing upon a foundation of mathematical physics.

Her last major study, *Microscopic and Molecular Science* (1869), perhaps her most speculative work, was published when she was 89. And here one sees the fruits of formidable reading and corresponding, as she wrestled with ideas of how matter cohered together to form atomic and molecular structures. It covered recent theories of chemical action, the fundamental rôle of gases, electro-magnetism, and the new science of spectroscopy, and much was said on the puzzling subject of the endless source of solar heat and radiant energy. And while a 'secondary source' in itself, being based on interpreting the researches of others, it is nonetheless a masterpiece of physical synthesis, and still probably stands unique today as the achievement of an 89-year-old!

Indeed, Mary's fascination with science and technology never abated, and when, as a very old lady, she was the honoured guest at a reception aboard *HMS Resistance*, commanded by her nephew Captain Henry Fairfax, which was then visiting Spezia in northwest Italy, she requested a full tour of the new iron-clad ship, descended into the engine room, and inspected the great screw propulsion shaft, the great breech-loading rifled guns, and other state-of-the-art features of a Victorian battleship — features that, perhaps, not every visiting elderly aunt would wish to examine!

In spite of her obvious mathematical genius, however, Mary Somerville made no single major discovery, and her contemporary fame lay in her ability to digest and present vast bodies of physics-related science in a series of magisterial volumes and grand syntheses. That has led some writers to speculate what she would have achieved had her sex not kept her out of the job market and prevented her from holding a major chair.

It is all too easy, however, from our present-day perspective, to forget how few major academic jobs existed in Victorian Britain, how indifferently paid many of them were, and how their male incumbents generally needed some sort of private income — derived from popular lecturing, writing, an ecclesiastical benefice, separate consultancy work, or an inheritance — if they were going to enjoy a good standard of living. For high-level British scientific research 150 years ago was not state- or academically-funded. It derived instead from the 'Grand Amateur' self-financed tradition, with people like Sir John Herschel, Lord Rosse, or William Lassell paying their own way and investing vast sums of their own money, and personal time, in developing and perfecting new research technologies. Mere professors were the 'cart-horses' of science, over-burdened with teaching or routine observatory duties and often working with slightly old-fashioned instruments, which excluded them from the latest researches; whereas it was the independent, rich 'Grand Amateurs' who were the fast-racing 'Derby winners' of discovery, and who stood at the forefront of research. One need only look at the Fellowship lists of the early RAS and Royal Society to see how few of the scientific 'leaders' held full-time academic posts before the 1870s.

Far from being excluded because of her gender, therefore, I would argue that the open, free 'personal contacts' rather than bureaucratic hierarchy basis of British science gave Mary a social mobility and a platform that would have been much harder to achieve in France, Germany, Austria, or Russia. For in those countries, science was already much more 'professionalized': often state-funded, bureaucratically-organized, and demanding the possession of the new PhD research degree if one were going to rise and shine in the hierarchy. That is why Mary Somerville, along with Caroline Herschel, Ada Lovelace, Margaret Huggins, Agnes Clerke, Elizabeth Brown, and other Georgian and Victorian scientific women, was very much of a British phenomenon. Only in America, with its own early 'Grand Amateur' tradition, and private Liberal Arts Colleges — including Vassar for women — does one also find the emergence of serious scientific women: women who lived in social circumstances rather similar to those of their British sisters.

Mary Somerville died on 1872 November 29, quietly and peacefully, after correcting some proofs, and apart from some deafness, in full possession of her faculties. She joined her husband William in the English Cemetery in Naples. And as the foremost female intellectual icon of the age, she won an enduring memorial when, in 1879, Oxford's new women's college was named in her honour.

The President. Thank you very much! Your lecture reminds us that whilst we have made a lot of progress in women's contribution to science and so on, we still have some way to go, but also we need to keep our eyes on the other minority groups, which haven't even got as far as that; so thank you for those reminders, Allan. Are there any questions?

Professor P. Murdin. Could you say something about Mary Somerville's rôle in the discovery of Neptune?

Dr. Chapman. She didn't really have a big part in it, but she certainly corresponded with John Herschel on the idea of there being another planet. You see, a couple of years before the discovery of Neptune, Herschel actually said, in his Presidential Address to the British Association, that it is likely we are going to find something beyond Uranus in the near future; and she was a close correspondent of his — they corresponded for over half a century. I think you had so many people in France, Germany, and England especially, who were of the opinion that there was something 'out there', and by that time you have a lot of correspondence; and while she did nothing original herself, in the form of a calculation, nonetheless she was part of that informed circle.

I can tell you one of the extraordinary things in her letters with Herschel: in the 1860s, when of course the spectroscope had just been introduced, Herschel sent her an account of trying to get the spectrum of a rotting fish in the kitchen — that was in the days before electric light, and no light pollution: a rotting fish, phosphorescent in the kitchen, and he tried to get a spectrum! [Laughter.] And he wrote and told Mary Somerville about it.

The President. Thank you very much, Allan. [Applause.] So we now move on to the two thesis-prize talks. The first one is by Baojiu Li, the Michael Penston Prize-Winner for 2009, who will talk to us about 'Physical and cosmological implications of modified gravity theories'.

Dr. B. Li. Let me first briefly introduce the motivation for studying modified gravity (MG) theories. Recent observations show that, according to our standard theory of gravity, about three quarters of the matter in the Universe is in the form of dark energy, which drives an accelerating expansion of the Universe; another fifth is in the form of dark matter, which dominates in the galaxies and galaxy clusters. As a result, normal matter, including baryons, photons, and massless neutrinos, only contributes ~ 4% to the total energy budget and this poses a serious naturalness problem for many people, which drives them to consider an alternative: as dark energy and dark matter take effect on very large scales, and General Relativity has only been rigorously tested in the Solar System, it is possible that there only exists normal matter, but gravity is not as we understand (at least on large scales).

General Relativity (GR) is mathematically formulated by Einstein's equation $G_{\mu\nu} = T_{\mu\nu}$. On the left-hand side we have the Einstein tensor, which describes the geometry or curvature of the space–time; on the right-hand side we have the energy–momentum tensor, which encodes all the information about the matter distribution. The equation therefore tells us how the space–time geometry responds to the matter distribution. When applied to cosmology, it gives the Friedmann equation $3(\dot{a}/a)^2 = \rho$ (a is the size of the Universe and $\dot{a}$ represents the time derivative), which describes how fast the Universe expands given the average matter density ρ. In the standard framework we add new exotic matter species (dark matter/energy) to the right-hand side, while in MG theories, in contrast, we modify the left-hand side, keeping the right-hand side of the equation unchanged.

The MG theories are featured by a rich phenomenology. There are numerous ways to modify gravity, many of which do not even lead to healthy theories (*e.g.*, free from instabilities). Also, MG theories usually need different treatment from that of GR, which is often ignored in the literature. Furthermore, some of the MG theories involve high degrees of nonlinearity, making both analytic and numerical studies particularly difficult. In addition, as most MG theories are proposed to explain the observed accelerating expansion of the Universe, they are often not sophisticated enough to agree with all other known observations, which can then be used to test those ideas.

As an example why naïve treatment which applies in GR does not necessarily work for MG theories, consider the so-called Palatini $f(R)$ gravity. Instead of the Friedmann equation $3(\dot{a}/a)^2 = \rho_m + \rho_{DE}$ of GR, where ρ_m and ρ_{DE} are respectively the densities of matter and dark energy, this theory is governed by a modified Friedmann equation $3(\dot{a}/a)^2 = [\rho_m + V(\rho_m)]/F(\rho_m)$. As promised, there is no dark energy in this equation, but gravity is modified by the two nonlinear functions V and F, which are specified in a given model, and which play the rôle of ρ_{DE} in GR. In GR, the average density ρ_m is calculated by dividing the total mass of all the particles (say atoms) in a volume by the volume, and this seems to be the approach followed in the $f(R)$ literature as well. However, there is a problem with this approach: because the modified Friedmann equation is fundamental, it is supposed to apply on microscopic (*e.g.*, atomic) scales, which means that instead of using $F(\langle\rho_m\rangle)$ and $V(\langle\rho_m\rangle)$ in the equation, we should use $\langle F(\rho_m)\rangle$ and $\langle V(\rho_m)\rangle$ when applying the equation to macroscopic scales (*e.g.*, the Universe). This leads to completely different behaviour of the theory because F and V are nonlinear functions of ρ_m. Therefore, in general, one must be careful to check the validity when applying the familiar methods of GR to MG theories.

A primary example of the high nonlinearity of MG theories is that they often present strong environment-dependence (ED). Indeed, the presence of ED is often an indication that the given MG theory could be practical. To see this, recall that GR has been tested with high precision in the Solar System, and we do not want any MG theory to spoil this success, which means that it should behave exactly as GR in the Solar System and only have deviations on much larger scales (*e.g.*, in galaxies and beyond). The mechanism by virtue of which the theory behaves differently in different environments is often called the chameleon mechanism.

Obviously, the theory must be able to realize and distinguish amongst different environments, and this is often achieved by testing certain dynamical quantities. The first type of chameleon mechanism to be mentioned works by using the local matter density as the flag of the ED. In GR, the gravitational potential Φ (and thus gravity) is determined by the local matter density $\delta\rho_m$ according to the Poisson equation $\nabla^2\Phi = \frac{1}{2}\delta\rho_m$. In the so-called metric $f(R)$ gravity, in contrast, we have a modified Poisson equation $\nabla^2\Phi = \frac{1}{2}\delta\rho_m - \nabla^2 F$, in which F is a new dynamic degree of freedom, the dynamics of which is controlled by $\nabla^2 F = -\frac{1}{3}[V(F) + \delta\rho_m]$. It could be shown that, if the nonlinear function $V(F)$ is chosen suitably, then the equation drives $\nabla^2 F$ to be very close to 0 when $\delta\rho_m$ is very big, and then the modified Poisson equation reduces to that in GR. This means that in high-density regions (*e.g.*, the Solar System, where GR has been accurately tested) the theory behaves essentially the same as GR and thus passes various experimental tests.

The second type of chameleon mechanism to be mentioned works by using the strength of local gravity as a flag of the ED. An example is the so-called modified Newtonian dynamics (MOND) model, for which the modified Poisson equation is given by $\nabla\cdot[\mu(|\nabla\Phi|/(a_0))\nabla\Phi] = \frac{1}{2}\delta\rho_b$. This model is designed to eliminate the need for dark matter in galaxies, and so we have only baryonic matter (ρ_b instead of ρ_m). Here $\mu(x) \equiv x/\sqrt{\{1 + x^2\}}$, a_0 is a constant and $|\nabla\Phi|$ is the strength of the local gravitational field. In strong local gravitational fields $|\nabla\Phi| \gg a_0$ so that $\mu(x)\to 1$ and the standard Poisson equation of GR is recovered; in weak fields $|\nabla\Phi| \ll a_0$ so that $\mu(x)\to x$ and gravity is modified. This model turns out to be very successful in galaxies. In the model building, to get this modified Poisson equation, we have a dynamic field F which tracks $|\nabla\Phi|$ and this field is used to control the on and off of the chameleon effect. It turns out that the field F also tracks the expansion rate $\dot{a}/a$ of the Universe, and the same modification also produces a modified Friedmann equation, which eliminates the need for dark energy as well.

Finally, let me mention briefly how the cosmological observables could be used to test MG theories, making the Universe as a whole an ideal laboratory to study the fundamental physics. The first example of such observables is the power spectrum of the cosmic microwave background, which is the relic of the hot Big Bang in the very early Universe: the modification to gravity could change the expansion rate of the Universe (thus the peak positions of the power spectrum) and the evolution of the gravitational potential on large scales (thus the magnitude of the power spectrum), and we find that this could place stringent constraints on certain classes of MG theories. The second example is the large-scale structure of the Universe: the current structures of our Universe (*e.g.*, galaxies, galaxy clusters) grow out of the very tiny density perturbations in the very early Universe, when the density was almost homogeneous, because if density is higher in a region, then gravity is stronger, further pulling matter from the environment into that region. The modification to gravity changes the strength of gravity and therefore the growth history of the density perturbations, a fact which could be used to constrain the different MG scenarios. There are many other observables, such as the weak gravitational lensing (deflection of light rays by the massive bodies in the Universe), which I shall not discuss here.

In summary, MG theories provide reasonable alternative frameworks to solve the outstanding cosmic puzzles in contemporary physics, and the increasingly precise cosmological observations have already started to produce high-quality data which are useful to test these, amongst many other, ideas. By combining theoretical and numerical analyses of the different MG theories, we could gain certain insight into what is required and what is not desirable in solving these puzzles. During the past few years, the studies of MG theories have become main stream, and we expect that with improving data quality and resolution in simulation, more could be done in the near future.

Professor M. Rowan-Robinson. The Newtonian approach doesn't seem very fruitful, given that we know that clusters act as gravitational lenses, the binary pulsar emits gravitational waves, that black holes exist; surely it's got to be something closer to General Relativity to get anywhere?

Dr. Li. Well, for example, you cannot distinguish $f(R)$ gravity from General Relativity in places such as in the Solar System, or for pulsars or black holes. You can distinguish it from General Relativity only on very large scales.

Mr. M. Hepburn. Cooperstock, who was one of Rosen's last pupils, writes papers which appear in arXiv, where he claims, as far as I can understand it, that General Relativity as understood through the Friedmann interpretation is wrong, as Einstein thought. And by simply using General Relativity as interpreted by him and Rosen, going back to Einstein, you get very accurate correspondence with the observed galactic rotation curves. His papers are filled with quite the right sort of symbols and equations and so forth, but then nobody seems to understand them and nobody seems to have commented on them; have you studied those papers?

Dr. Li. No. [Laughter.]

The President. It's a short answer! Thank you very much!

The President. The final talk today is from the 2009 Keith Runcorn Prizewinner, David Halliday, from Schlumberger Research Centre and the University of Edinburgh, and his talk is entitled 'Surface-wave interferometry for earthquake and exploration seismology'.

Dr. D. Halliday. Typically seismologists study recordings of seismic waves that have been excited by a source of seismic energy that is well defined both spatially and temporally. For example, earthquake seismologists study recordings due to earthquakes, and exploration seismologists study recordings due to controlled sources such as vibrators or dynamite. As such, many of the tools for processing seismic data rely on knowledge of both where the seismic waves came from, and where the seismic waves were recorded.

One particular type of seismic wave is the surface wave, which (as the name suggests) travels laterally through the surface (or upper part) of the Earth.

For the earthquake seismologist this is an important source of information. Surface waves excited by earthquakes with a period of less than one second are particularly sensitive to the structure of the Earth's crust and the upper mantle, and hence can be used to create models of the geological structure.

On the other hand the surface wave is considered as a source of noise for many exploration seismologists. Typically exploration seismology deals with waves with a frequency from one to one-hundred hertz. At these frequencies the surface wave only travels through the upper hundred metres or so of the Earth. The target of interest in exploration seismology can be several kilometres beneath the surface of the Earth. In this context the surface wave carries no useful information and is treated as a source of noise that must be separated from the rest of the data.

Seismic interferometry is a relatively new approach to seismic-data processing that allows seismic data to be looked at in a different way. The novelty of seismic interferometry is that no information is needed about the source of the seismic waves. Instead the seismic waves are recorded at two (or more) receiver locations. The waves observed at one receiver location are combined with those recorded at the other by cross-correlation (a mathematical tool that looks for coherency between two datasets). Provided that the waves recorded have travelled from a suitable range of directions, the remarkable result of this process is a recording of the waves at one of those receivers as if a source had been placed at the location of another receiver. This method is particularly suited for application to surface waves.

Application of the method to surface waves is desirable in a number of cases. For example, consider a land-mass such as the United Kingdom that sees very little seismic activity. It is difficult to create models of the crustal structure of the UK using conventional seismic-processing methods because there are not enough well-defined sources of seismic waves (the earthquakes). However, the UK is surrounded by two sources of seismic surface waves that are acting constantly — the Atlantic Ocean and the North Sea. Neither of the sources has a well-defined location, or a defined start time. But, by taking advantage of the network of seismic-recording stations throughout the UK, seismic interferometry can be used to extract meaningful information from the surface waves excited by the oceans. These waves are treated as a source of noise in conventional seismology, but seismic interferometry allows them to be used to create detailed models of the upper crustal structure of the UK (and many other regions around the world).

You might think that there is little application for this method in exploration seismology, since I mentioned earlier that the surface waves are treated as a source of noise in the exploration domain. This is not the case. We know that seismic interferometry is particularly suited to surface waves and what has been observed in both theoretical and data studies is that the surface waves extracted using seismic interferometry are almost completely separated from the other wave types. These other wave types might include refracted or reflected body waves which carry important information about the deeper part of the Earth (for example a hydrocarbon reservoir). This means that seismic interferometry can be used to create a surface-wave-noise reference, which can be used to separate surface waves (the noise) from reflected body waves (the signal). This is similar to the technology used in noise-cancelling headphones, where the sounds coming from outside the headphones (the noise) are separated from the sounds played by the headphones (the signal). Here I should note that the waves used in interferometry can still be man-made. In this noise-separation problem the inputs to surface-wave interferometry are recordings of waves excited by a number of vibrating trucks.

One of the reasons that working with surface-wave interferometry has been so rewarding is that it has been possible to work on both earthquake-seismology problems and exploration-seismology problems within the confines of the same project. The surface-wave application I described here is one of the first successful applications in exploration seismology. There are many other applications in the literature, with new uses of the method appearing almost on a monthly basis. Finally I note that the method is not limited to surface waves: there are also many promising applications using body waves both in earthquake and exploration seismology.

The President. Thank you, David. Any questions?

Dr. G. Q. G. Stanley. With the detectors that you have on the surface, have you used them where they are buried or at the tip of a well head or something like that, so you can get a 3-D-resolution signal with some at the surface and some at different depths?

Dr. Halliday. I've never seen anyone apply the method between the surface and the sub-surface. There are lots of applications where we have the receivers only in the borehole, so we bury the receivers much closer to a reservoir, or something like that in the subsurface. But I've not seen anyone try to combine borehole receivers with surface receivers.

Dr. Stanley. If we compare with the *Cluster* satellite mission, where we go between several satellites to pick up signals to obtain a 3-D resolution, it would be something similar to that; and if you have a mine, you already have a borehole, so you could obtain data with a very good resolution.

The President. I noticed that when you recovered the density of the rock from the North Sea experiment ...

Dr. Halliday. Yes, the measurement was the surface-wave group velocity.

The President. ... you found the sedimentary basin in the Severn Estuary; but are there other sedimentary basins in the UK, like the Wash, that you would have expected to pick up?

Dr. Halliday. I'm not sure, but the 7 seconds on the plot refers to a specific period or frequency and that period or frequency is sensitive to a certain depth in the Earth. So maybe the other basins that we're not seeing are shallower, or deeper, or smaller.

Professor Murdin. Along the same lines, the area in Normandy that is coloured blue in your figure, along by the Seine, those are chalk cliffs, so neither igneous nor metamorphic rocks.

Dr. Halliday. Have you noticed that the stations are predominantly in the UK? So we have very few paths between receivers crossing this point, so we have less confidence in the edges of the image.

Professor Murdin. So Brittany is like Scotland but the Seine Valley is not?

Dr. Halliday. Well, if that's how you interpret it! [Laughter.]

Professor Kathy Whaler. Roughly, what depth is 7 seconds? I mean, what do you think the practical depth limit is for noise sources? I know people can get natural sources that go to reasonably long periods now in surface waves, so you can get, as you were saying, well into the upper mantle.

Dr. Halliday. Yes, there's a rule of thumb for period *versus* depth, but I can't remember it!

Professor Whaler. But I think that's deeper than the structures that we're largely talking about here, the smallest sedimentary structures.

The President. Last question?

Mr. Osmaston. Am I right in thinking that the frequency you use affects the depth to which you are recording some information, and if so, what is the sort of typical depth to which you can go, and what is the frequency you are then using?

Dr. Halliday. All my experience is on the exploration-geophysics side — the lowest frequency that we put into the Earth through exploration is 2–3 hertz; and for a surface wave I think that penetrates a few hundred metres into the Earth's surface. In global seismology, we start at 1 hertz or so and work down.

Professor Whaler. I'm thinking about a number of tens of seconds, and then you are seeing into the upper mantle, so you're seeing several hundred kilometres down by recording at, say, 20–30 seconds; that's my recollection, but I'm not a seismologist!

The President. Let's thank David again! [Applause.] So just to wrap up, let me remind you there is a drinks reception over in the apartments now, and we will meet again at the Ordinary Meeting of the Society on Friday, February 11.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2011 February 11 at $16^{h}\ 00^{m}$
in the Geological Society Lecture Theatre, Burlington House

R. L. Davies, *President*
in the Chair

O. Lahav, *Vice-President*

The President. You will probably have heard, on the news this morning, of the new strategic arrangement between Microsoft and Nokia — that doesn't mean you can leave your mobile phones switched on, so please switch off your mobile phones now so that we don't have any interruptions! [Laughter.]

The first talk this afternoon is by John McCloskey, from the Environmental Sciences Research Institute in Ulster, on 'Plate interface coupling and tsunami hazard'.

Professor J. McCloskey. My job is essentially to help people to prepare better for unpredicted events. I believe we can locate hotspots of activity and we want to see how specific parts of this hazard can be identified.

The USGS website contains records of historical earthquakes, and since 1556 there have been five really big events with the 1556 event being the most violent of all. However, two of the others have been in the last five years and three in the last 30 [Editors' note — this does not include the Japan event of 2011 March 11] so the vulnerability of communities around the world is becoming more severe. Most of us in the field are convinced that in the next ten or twenty years we will see the first earthquake to be responsible for one million casualties.

My main interest is subduction-zone earthquakes in the area of N. W. Sumatra, particularly near Pedang where the Indian and Australian plate is being pushed under Sumatra. It does not slip smoothly, but sticks, building up a lot of strain and resulting in earthquakes. After each of these we get recovery of the deformation almost immediately — a bulge forms driving the surface water upward resulting in a tsunami which then hits the shoreline. This was shown most graphically in 2004 when the town of Bandar Aceh was covered to a depth of 15 metres because it was low-lying, resulting in many of the people living there being killed. Why is this area at particular risk? The previous history can be gleaned from the growth patterns in corals which act as 100-year strain readers and map the resulting vertical displacement. In 1797 there was an earthquake of magnitude 8·7 and the resulting tsunami wave height was 5–6 metres. Today 750 000 people live within 10 metres of sea level so the potential death toll of a similar event would be half a million people, potentially much worse than 2004.

With modern techniques we can measure the slip very accurately but the difficulties come in trying to predict what will happen afterwards. We need information on the magnitude of the earthquake and how the land slips — these can be integrated in order to get the amount of energy released. Numerical simulations of tsunamis depend on the position of slip, and the estimated wave height might vary by an order of magnitude depending on whether the slip occurs offshore or onshore. As we cannot predict the slip distribution in the earthquakes, it is better to choose a series of high-probability earthquakes and use Monte Carlo methods to make estimates of tsunami heights. How can we constrain the slip distribution? The distribution of wave height will also depend on how the plates are coupled between earthquakes. When they are stuck tight there is a lot of accumulated energy which is released quickly.

In Japan there is a superb array of GPS sensors which are being used to try and understand the movement of the crust. Fabrizio Romano looked at the Tokachi-oki earthquake of 2003 with these data and applied a chequerboard slip distribution to an imaginary faulting under the water and then applied the tide-gauge data to recover the original slip distribution. In addition, pressure gauges on the sea floor show good prediction inshore but lose resolution offshore. Only when you invert the data from the GPS, pressure gauges, and tide gauges do you recover the target slip-distribution properly. This technique was used last year for an earthquake in the Darwin gap — an area in Chile where Darwin observed an earthquake in 1835. Here, nearly all the energy is being stored in the interface and the energy of the interface coupling has been measured. The idea of a simple plate-interface model is attractive but it doesn't always recover the data properly. We can measure the stress distribution in the Darwin Gap and a pressure of 20 bars has built up there — there could be a severe earthquake soon. Again we are trying to see how the coupling is related to the slip distribution and whilst high coupling is necessary for high slip, it is not a strong constraint.

Our best forecasts at the moment are still falling short of making strong statistical predictions. The concept of interface coupling is good but we do not understand it yet.

The President. Thank you very much. Questions?

Dr. R. C. Smith. I was puzzled by something you said about Chilean earthquakes: you had this coupling distribution, and there are actually two peaks at 0·85, shown at the top, the northern one; did this actually coincide with the slip distribution?

Professor McCloskey. The peak in the slip distribution, of up to 20 metres, overlaps slightly with that; the 20-metre slip is actually in an area which is coupled by about 0·65. So it's still not weak coupling: there is still a lot of strain energy that has been accumulated there. The main thing that surprised me about that earthquake was that the high-slip patch overlapped completely the 1928 earthquake. So there is something around there that happened before 1928 that sets the game off — something that you could not have forecast without our present understanding of this system. So yes, in fact the 0·85 to the north captured more than the 0·85 in the centre, but it's still not a good correspondence.

The President. One more question?

Mr. H. Regnart. Speaking with the unfair disadvantage of near total ignorance, if the magnitude quantity in orientation of micro-cracks are relevant in the run-up to an earthquake, might a concept of a supercooled liquid and a sudden phase change be relevant to the sort of thing that you are doing?

Professor McCloskey. I really don't think that supercooled liquids are going to help, but one technique which was discussed over the last few days was the importance of micro-cracks, and fluids within those micro-cracks, because the propagation of seismic waves, particularly the polarization, is affected strongly by fluids found in microcracks, and the delay of the micro-cracks' polarized seismic waves is really sensitive to stressing, so we can, we believe, use fluid-filled micro-cracks and their effect on the polarization of seismic waves to measure the stresses. But it is worth pursuing — it's way up at the cutting edge.

Mr. Regnart. What I was thinking of is that you have a supercooled liquid, say distilled water, and it's below its proper freezing point, and then a phase change to ice might happen very quickly. That might provide a useful analogy to what happens when the pre-cursor state actually becomes an earthquake and the stress is released.

Professor McCloskey. I think the idea of phase changes in earthquake geophysics is really fundamentally important. The statistics of earthquake populations are exactly the same as the statistics for second-order phase changes. I think that there is a lot of work to be done on that. We appear to be looking at the statistics of a critical-point phenomenon. So it means that the effects of these events are far more unpredictable than we think.

The President. On that note, I think we had better say thank you again. [Applause.] Our second speaker is Mark Birkinshaw from Bristol: 'Johannes Hevelius, the Prussian Lynx at 400'.

Professor M. Birkinshaw. Johannes Hevelius (the Latinized version of his name) was born in Gdansk 400 years ago this year, at the beginning of a turbulent period of wars and invasions that shrank the Polish empire until the recovery late in the 17th Century. In Gdansk, Hevelius was isolated from much of this turmoil, though not entirely unaffected by it.

At the beginning of the 17th Century astronomy was seeing rapid change — in 1611 Kepler described improvements to the telescope, and the *Sidereus Nuncius* of Galileo had come out. Jan Höwelcke was born on 1611 January 28, the second of ten children in a family of well-to-do brewers — an important profession in an age where safe drinking water was difficult to get. Jan was educated at home and then attended the Danziger Akademicum Gymnasium until it closed for three years from 1624. At that time he was sent to Bydgoszcz, then known as Bromberg, possibly to help him learn Polish, as he had been brought up speaking High German. When the Danziger Akademicum reopened he returned and came under the influence of Peter Crüger who was a gifted astronomer but also partially blind. In 1630 Hevelius travelled to Leiden to study law, observing the June 10 solar eclipse *en route*, but he never completed his studies, instead travelling on to London in 1631, where he seems not to have picked up much English but met several astronomers. He then went on to Paris where he met Bulliadus and Gassendi, and to Avignon, where he encountered Kircher, before heading for Italy with the intention of meeting Galileo; but he was called home to help his father with the brewery, and he returned to Gdansk, where he was to stay for the rest of his life.

In 1638, four years after marriage to Katharina Rebeschke, he bought a 6-cm telescope made by Scheiner with which he made observations of sunspots. In 1639 he inherited some of Crüger's instruments, and observed the eclipse of June 1. He built a small observatory on the roof of one of the family houses and observed for the next few years, in 1645 building the largest optical telescope then in existence. The year 1647 was a landmark, when he published *Selenographia, sive Lunae descriptio*. This significant volume includes instructions on how to make a good telescope lens, but is important mostly because it contains the first really detailed maps of the Moon and a description of lunar libration. Hevelius' names for the lunar features, based on analogy with features on the Earth, have mostly been discontinued, though some, such as the lunar Apennines, are still in use. *Selenographia* also contains Hevelius' observations of sunspots and how they change with time. These have recently been studied because they lie within the Maunder minimum — the fact that they are still of scientific use is a measure of the accuracy of his work.

In 1649 Hevelius senior died and Jan inherited the family fortune — including seven houses and the brewery. He expanded his observatory considerably, to extend over the roofs of three houses, and renamed it Sternenberg. Two years later, as a prominent merchant, he became a permanent member of the City Council but continued to work at the observatory. Four years later he embroiled himself in an argument about the nature of Saturn's ansae. Huygens thought them to be part of a ring while Hevelius argued that they were telescopic aberrations.

After the death of his wife in 1662, and the publication of another important book, this time on Mira, Hevelius married Elisabetha Koopmann in early 1663. Although she was 16 and he was 52 the marriage seems to have been long and happy. In 1665 he produced a handbook on comets and another controversy — this time about the coordinates of the comet of February. The Royal Society (of which Hevelius was elected a Fellow in 1664) investigated and decided Hevelius was wrong — but he argued differently in his *Cometographia*, published in 1668. This was followed in 1673 by *Machina Coelestis, pars prior*, the frontispiece of which is over-heavy with symbolism, including the eye of the Lynx, a symbol of excellent vision with which Hevelius identified himself.

The *Machina Coelestis* discusses the problems that Hevelius had with lenses, and recommended naked-eye viewing. While Flamsteed considered this a limitation, it attracted attack from Robert Hooke in a series of lectures and his *Animadversions on the First Part of Hevelius' Machina Coelestis*. By way of judging the matter, Edmond Halley visited Hevelius in 1679 to assess the accuracy of Hevelius' work. He found that Hevelius' data were more consistent than those obtained with his own travelling sextant, which was built according to the precepts laid down by Hooke. Hevelius had the benefits of experienced observers helping him — his printer and wife were both highly skilled — but he was also using some of his own developments, of good clocks and improved screw drives and vernier scales. During this visit to Gdansk, Edmond Halley saw the 60-foot 'aerial' telescope, and noted that the largest examples of such telescopes were largely useless for practical observing. Despite preferring naked-eye viewing, Hevelius did own more conventional refractors that he used for some purposes.

On 1679 September 27 Sternenberg was destroyed by fire. Almost everything was lost, except for a copy of the star atlas on which Hevelius had been working for many years. The instruments, all seven houses, and his private printing press with the copper plates for his spectacular artwork were destroyed, except for a single copper printing-plate of the Moon. His family was, much later, to convert that into a tea-tray, but has since lost track of it completely. Hevelius' account of the disaster in his 1685 book *Annus Climactericus* is followed by his description of Halley's visit and an account of his rebuilt (and inferior) instruments, with some results from using them.

Hevelius died on his birthday in 1687, leaving notes for further books that would be published in 1690 by Elisabetha after unsuccessful attempts to get help from the Royal Society with completing the work. These final books, the *Prodromus Astronomiae* (Guide to Astronomy) and *Firmamentum Sobiescianum* (Sobieski's Sky, named for the ruling family in Poland) are somewhat different in style from the earlier books — and I believe that some of the material was written by Elisabetha with help from Joannis Ernesti Schmieden.

Elisabetha died in 1693, but the Hevelius brewery continued until the 1990's when it was taken over by a large Danish firm [laughter]. We owe a debt to Hevelius for his work on Mira and the Moon, and it is fitting to remember him this year. [Applause.]

The President. Questions?

Mr. M. Hepburn. Is the constellation Lynx one of his?

Professor Birkinshaw. Yes it is, that's right! He named eleven constellations. Four of them were obliterated in the change in constellation names, but still seven bear his names.

Dr. A. Chapman. An excellent talk, thank you! Three observations — not criticisms, but observations! The first of these: I am fascinated by the iconography of Copernicus, Tycho Brahe, and Hevelius. And I think there was a global awareness, certainly on the part of Tycho and Hevelius, of what one might call a 'Northern Renaissance' or a 'Baltic Renaissance'. And I think this could be the very clue to interpreting the superb iconography of Tycho and especially of Hevelius. Secondly, there were long telescopes after 1650, with which the Dutchman Christiaan Huygens discovered the true nature of the 'ansae' of Saturn. Indeed, Robert Hooke, Giovanni Domenico Cassini, and others quickly went on to make a number of further discoveries with long refractors, such as Jupiter's belt systems, Saturn's satellites, the Cassini division, the polar caps and Syrtis Major on Mars, the outline shape of the Orion Nebula, and so on. And modern reconstructions of long telescopes — albeit 15–20 feet instead of 60 or 100 — have shown that under the right conditions and in stable air quite a lot of planetary detail can be seen with them.

Professor Birkinshaw. Absolutely, but there is a difference between the ones that are about 12 feet long and the ones that are over 140 feet long.

Dr. Chapman. Of course, Robert Hooke in London in the 1660s used 36- and 60-foot-long refractors to make the first detailed drawing of a single lunar formation, the crater Hipparchus (*Micrographia*, 1665). And when you compare that drawing with a modern photograph of Hipparchus, it is amazing to see the detail and accuracy with which Hooke recorded it. So I think, given patience and the right viewing conditions, those long telescopes really provided a lot of new, original data. And Johannes Hevelius, and his contemporaries across

Europe, did *not* — as popularly supposed — build those monster telescopes simply to reduce chromatic aberration. Rather, a very-long-focal-length object-glass gives a large prime-focus image, and was the best way, in 1660, given the relatively poor quality of available lenses, of obtaining high magnifications. And as 17th-Century astronomers were concerned with planetary-surface studies (being fascinated at the prospect of the planets being inhabited), long refractors were seen as the likeliest way of finding out whether the planets were continent-and-ocean-covered worlds like our own Earth.

Lastly, on my very great friend and 'biographical victim' Robert Hooke, on whom I have spoken quite a bit, I believe from his *Diary* he was a tremendously sociable figure with a real gift for friendship. He loved company, he loved an argument, and he also loved a scrap. And when he was corresponding with Auzout in Paris or with Cassini or Hevelius in Danzig, he enjoyed having an argument. He was, however, quite miffed when Auzout pointed out that his visionary great refractor of 10 000 feet focal length was a practical absurdity. But I don't think that he was at all an unpleasant or particularly difficult figure.

Professor Birkinshaw. Yes, but I think some of the people with whom he had a scrap enjoyed it rather less [laughter]. But I entirely agree with you about the iconography of the books from Brahe to Hevelius. The notion of putting out good-looking artwork, that showed that northern Europe could produce works of art of the same quality as those coming out of Italy, was extremely important.

The President. Last question, David?

Professor D. Hughes. Isn't it rather surprising that in 1687 the Royal Society didn't get in touch with Elisabetha? Because wasn't Edmond Halley at that time the Secretary of the Society, and therefore writing letters to his girlfriend was his job [laughter].

Professor Birkinshaw. I don't know whether the correspondence has been lost — there is nothing in the last books to indicate that there was any help from outside. And MacPike tried to work through the archives 30 or so years ago and couldn't find any trace of it.

Professor Hughes. He made a list of all Halley's letters.

The President. We should call it a day there, I think, so thank you very much Mark. [Applause.]

The Vice-President. Thank you, I am Ofer Lahav, one of the Vice-Presidents of the Society, and I am chairing the last session for a very good reason. It is a great pleasure to invite Professor Roger Davies, the President of the RAS, to give his Presidential Address, and the title is: 'Towards a new paradigm for early-type galaxies'.

Professor R. Davies. [It is expected that a summary of this talk will appear in a future issue of *A&G*.]

The Vice-President. A very good talk! Questions? Donald.

Professor D. Lynden-Bell. First, could you just explain to me what you mean by σ_r and σ_z, because there are two ways of defining σ_r: one is radial from an axis, and the other one is radial from the centre. Are you taking it from an axis?

Professor Davies. Yes!

Professor Lynden-Bell. Do you know what would happen if you tried using the radial from the centre?

Professor Davies. Not off the top of my head! We haven't done those models.

Professor Lynden-Bell. Well, let me just say what I think is an interesting remark: that if you take something like you find in the galaxy, whose anisotropy points more or less to the centre, rather than the axis, then there is not much pressure, round-and-round, there is only pressure radially, and when you have something that does not have much pressure round-and-round, even a small amount of rotation can flatten it a lot. So, the original result is not too surprising if in practice the anisotropy is basically radial, in the sense of radial to the Sun.

Professor Davies. I agree completely. Why do we think that the cylindrical model is the right one? One reason certainly is that if you look at bulges, it is clear that the velocity dispersion of bulges, the cylindrical dispersion of bulges, doesn't vary very much as a function of distance out of the plane, so that suggests that you have got something with cylindrical symmetry rather than spherical symmetry; but you know, it's a detail.

Professor J. Barrow. How different is the degree of isolation of these objects? I mean, some of them feel more significant perturbations from near neighbours than others?

Professor Davies. Yes, absolutely, but they are not isolated. There are very few objects that you can use the word 'isolated' to describe. So there is about a factor of a hundred in the density parameter that I showed. And in the densest regions you are at another factor of a hundred denser than that.

Professor Lord Rees. I have a question on the mergers. You imply that the numbers in simulations worked out more or less right. Would those mergers have happened when the clusters assembled, or before that when the relative velocities of the galaxies might have been smaller?

Professor Davies. I think almost certainly before that, yes. On the way in — I think — is the likely scenario. In fact I didn't mention it, but there is a parallel modelling effort going on in this project as well.

Mr. M. F. Osmaston. Out of the thirty two, are there any non-red ones?

Professor Davies. No, they are all red and dead.

Dr. G. Q. G. Stanley. You have followed the paradigm that 'less is more', where your lambda is telling us much more than what we have with standard morphology, which is wonderful. I noticed that the SAURON and your Atlas survey analyses you presented both gave the ratio between the slow rotators and fast rotators to be about a factor of three. Do you feel there is a reason for this factor of three?

Professor Davies. You have to be careful here because you see all these numbers here are a function of mass, so — given the fact that the slow rotators are very much more concentrated in the most massive ones — as you go down to less massive ones you get a lower and lower fraction of slow rotators. So the fraction is just a result of how far and how faint you go.

The Vice-President. Just a quick question on those fantastic data that came back, plus the multi-wavelength observations. Can you get us the ratio of baryonic material to the mass relative to the cosmological ratio? About 16 percent, I guess. You probably get smaller numbers?

Professor Davies. Yes, we can do that, and we are doing that now, so you can track that. In fact we can do that at different radii. So this is work in progress, but typically, within one effective radius we are finding ten to twenty per cent of dark matter. But if you go to two effective radii that number goes up to thirty or thirty-five per cent.

The Vice-President. Let us thank Roger once more! [Applause.] The next monthly meeting of the Society will take place on March 11th.

EXPLORING α CENTAURI: FROM PLANETS, TO A COMETARY CLOUD, AND IMPACT FLARES ON PROXIMA

By Martin Beech
Campion College, The University of Regina

A brief overview of the α Centauri system is presented, and the possibility that planets and a cometary cloud might have formed about α Cen AB is considered. We also review the rotational and flare-activity characteristics of Proxima Centauri. On the basis that Proxima is coeval with α Cen AB, having an age therefore between 5 and 7 Ga, it is found that Proxima's very slow rotation period, amounting to some 83 days, is consistent with a Rossby number of order 0·4, and that its surface magnetic field is generated *via* the α^2 dynamo mechanism. The impact hypothesis is further revisited in order to determine if the flare activity associated with Proxima might be explained and/or modulated through planetesimal accretion. Using Oort Cloud characteristics as an analogue, it is found that the impact rate on Proxima is probably too low to account for its overall flare activity — it is just possible, however, that impacts might induce an approximate half-decadal modulation in Proxima's activity cycle.

Introduction

No matter what one chooses to call it, Rigil Kentaurus or Toliman, α Centauri is a remarkable star system. Its relative closeness was first established through parallax measurements made by Thomas Henderson[1] at the Cape of Good Hope Observatory in South Africa between 1832 and 1834, and at the present epoch it is the fourth-brightest star visible to the unaided eye in the night sky. For at least the past 50000 years it has been the closest star system to our Sun[2], and it is still moving towards its point of closest approach, which will be achieved some 27400 years from the present[2,3]. Moving an additional 72000 years into the future, Ross 128 will finally depose α Centauri from its long-running sovereignty as nearest neighbour[2–4].

It is not clear who first resolved α Centauri into a binary pair, but it seems that Jean Richaud first noted its twinned nature on 1689 December 19 while observing a bright comet from Pondicherry, India, with a '12-foot' telescope. Certainly, by 1752 Nicolas de la Caille was making astrometric observations of the system as part of his survey work for the *Coelum Australe Stelliferum*, and John Herschel made micrometer measurements[5] of the components in 1834. Finsen[5] published the first orbital elements for the system in 1926 and the most recent elements[6] indicate an orbital period of just over 79 years (see Table I). The components of α Centauri are, respectively, 0·1 $M_{\odot}$ more massive (α Cen A) and 0·07 $M_{\odot}$ less massive (α Cen B) than our Sun, making it a near double-sol analogue. Not only this, however, α Cen AB may also form a triple system with the faint flare star Proxima Centauri (see Fig. 1, and Table I), which was discovered not quite one hundred years ago, in 1915, by R. T. A. Innes[7,8].

TABLE I

Orbital elements for the α Centauri AB binary and its close companion Proxima

	α Centauri AB	*Proxima Centauri*
Semi-major axis (AU)	23·68 ± 0·06*	272212·148
Eccentricity	0·5179 ± 0·0008	0·985
Period (yr)	79·1 ± 0·01	—
i (deg.)	79·20 ± 0·04	150·9
Ω (deg.)	204·85 ± 0·08	197·81
ω (deg.)	231·65 ± 0·08	86·87

The data for α Cen AB are from ref. 6; the data for Proxima are from ref. 9 and are based upon the centroid values of observed quantities (see, however ref. 10 for a discussion concerning Proxima's most likely orbit given that it is truly gravitationally bound to and coeval with α Cen AB). *Semi-major axis determined according to a parallax of 742·12 ± 1·40 mas and an angular separation of 17·57 ± 0·02 arc seconds (see ref. 6).

While one star system or another must ultimately be our nearest spatial neighbour, the fact that at this epoch it is a system like α Centauri AB-(C?) is noteworthy. Indeed, it is remarkable that such a system should be found so close to us at all. Raghavan *et al.*[11], for example, find from a survey of stars located within 25 pc of the Sun that there are 454 Sun-like stars, and this suggests that a typical separation between such objects should be about 6·5 pc. Further to this, just 33% of the Sun-like stars studied by Raghavan *et al.* were found to reside within binary systems, suggesting that a separation of perhaps 13 pc is to be expected between the Sun and a binary system containing just one Sun-like component. To find α Cen AB, a double-sol analogue, just 1·35 pc away,

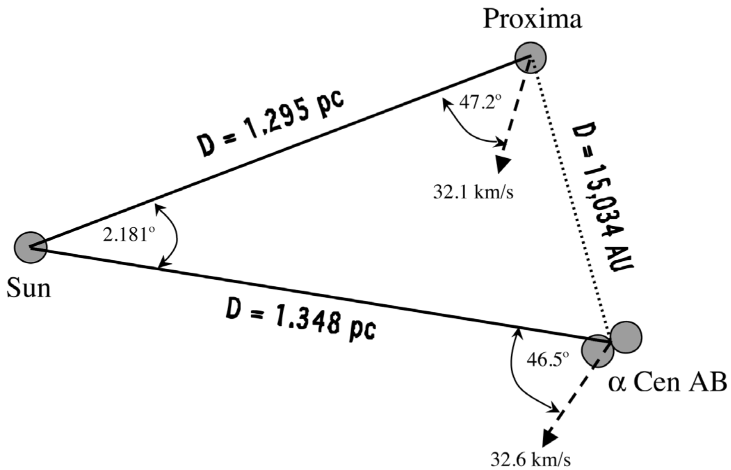

FIG. 1

Schematic diagram of the Sun, Proxima, and α Centauri AB system. The dashed lines represent the space velocities of Proxima and α Cen AB. The separations and various angles have been determined according to the parallax and proper-motion data given in the 1997 *Hipparcos Catalogue* (ESA). We note that Caballero[70] has recently applied the re-reduction of *Hipparcos Catalogue* data provided by van Leeuwen[71] to find a separation of 12 000 ± 600 AU between Proxima and α Cen AB, which is some 20% smaller than the value derived from the 1997 catalogue.

therefore, is fortuitous to say the least. In contrast to Sun-like stars, Gershberg[12] finds that the spatial density of flare stars in the solar neighbourhood is 0·056 per cubic parsec, which suggests that we should expect to find one flare star within the sphere of radius 1·6 pc about the Sun; accordingly, finding a star like Proxima at a distance of 1·3 pc is not particularly surprising. That Proxima should reside just 15000 AU from α Cen AB is, in contrast, thoroughly remarkable — indeed, the odds of such an arrangement coming about purely by chance[13] are about 1 in 57000.

In partial consequence of its relative closeness, intense interest has of late been focussed towards the search for possible planets within the α Centauri system[14–16.] Indeed, planetary systems may have conceivably formed around any one or all three of the stars. The orbital-element data presented in Table I reveals that α Cen A and α Cen B will periodically approach each other to within 11·4 AU, and this places strong constraints on the orbital location and stability of any potential planets. After performing a series of detailed numerical simulations, however, Weigert & Holman[14] found that any planets located within 4 AU of either α Cen A or α Cen B would have dynamically stable orbits, and there seem to be no specific reasons that terrestrial, indeed, habitable terrestrial planets could not have formed within our nearest neighbouring system.

α Centauri: system status and properties

The triple-system status of α Centauri AB and Proxima, while often assumed to be true in the literature, is far from being a proven result. The orbital elements for Proxima, based upon the centroid values of observed quantities, as recently derived by Wertheimer & Laughlin[9], are shown in Table I. This particular orbit is clearly not physically tenable since the semi-major axis is much larger than the tidal limit set by the gravitational field of the Galaxy, but as Wertheimer & Laughlin point out, the derived orbital elements are strongly dependent upon the value adopted for Proxima's radial velocity, and this quantity, at the present time, is not well determined. The orbital elements shown in Table I will no doubt change significantly as more and improved data are obtained, but at the present time all that might reasonably be said is that Proxima just straddles the region interior to which a gravitationally bound orbit is theoretically possible. Only if future observations find a radial velocity for Proxima just a few tenths of a km/s larger than presently reported[9,10,13] will its triple-companionship status to α Cen AB be reasonably established, if not assured. As a possible complicating factor to establishing this bound-state result, however, we note that it has been suggested[10,13] that Proxima's motion about α Cen AB should fall within the Modified Newtonian Dynamics (MOND) régime, and this effect, if it is real, will further muddle what is already a complex dynamical situation.

The physical characteristics deduced for α Cen AB-(C?) are shown in Table II, where it is immediately noticeable that the stellar masses and radii have been determined to impressive accuracy. The system age is less-well constrained, however, but recent studies find that α Cen A and α Cen B are likely to be of order 5 to 7 billion years old. Kervella *et al.*[17], for example, find a value of 4·85 Ga based upon isochrone fitting, while Guenther & Demarque[18] use different stellar models to find an age estimate of 7·2 ± 0·4 Ga. On the basis of asteroseismic data Eggenberger *et al.*[19] suggest an age of 6·52 ± 0·3 Ga for α Cen A.

Given an age commensurate to that of its apparent companions, amounting to 6 ± 1 Ga, Proxima is somewhat on the old side for being an active flare star. Indeed, Walker[20] has noted that Proxima has a high flare rate compared to other such stars of a similar age, but that the rate is on the low side compared to those flare stars of a similar luminosity. Walker[20] further emphasizes, however, that if Proxima were a young-disc star then it would be surprisingly under-active. West *et al.*[21] have more recently derived an age–activity relationship for the M-dwarf stars detected during the Sloan Digital Sky Survey and conclude that of order 70% of all M5V stars are active flare stars, and that the active lifetime for such dwarfs is of order 7·0 ± 0·5 Ga. What is particularly interesting about this latter result is that it implies that low-mass, fully convective stars (such as Proxima) are able to produce and maintain magnetic fields at their surfaces, and that given its estimated age, Proxima is possibly on the verge of entering its final flare-activity epoch.

TABLE II

Physical characteristics of α Centauri and Proxima

	α Cen A	*α Cen B*	*Proxima*
Spectral Type	G2 V	K1 V	M5·5 Ve
Luminosity ($L_{\odot}$)*	1·5	0·5	1·5 × 10^{-4}
Mass ($M_{\odot}$)#	1·105 ± 0·007	0·934 ± 0·006	0·123 ± 0·006
Radius ($R_{\odot}$)$	1·224 ± 0·003	0·863 ± 0·005	0·145 ± 0·011

*data from ref. 17; #data from ref. 6; $data from refs. 22 and 23.

Proxima as a flare star

It is now generally accepted[9] that flare activity is the result of a complex interaction played out between a star's magnetic field, the convective motion in its outer layers (described according to the convective turn-over time $\tau_{\rm conv}$), and its rotation period $P_{\rm rot}$. One measure that is often used to gauge the extent to which the convective motion is influenced by rotation is that of the Rossby number, where $R_o = P_{\rm rot}/\tau_{\rm conv}$. Observationally, the Rossby number is known to correlate with chromospheric activity[24,25], as indicated, for example, by Ca II *H* and *K* emission-line fluxes[26], with higher overall activity being associated with smaller Rossby numbers. In addition, Gilliland[24] has specifically demonstrated that there is a near-linear relationship between the logarithms of the $R_{\rm C\,IV}$–activity index and the Rossby number for main-sequence stars, and this allows for a consistency check, with respect to the apparent age and activity of Proxima, to be made — although, once again, the situation is not as clear-cut as one might have hoped for.

The combined effects of mass loss and magnetic-field generation result in the now well-established spin-down-with-age relationship for main-sequence stars[12,27]. Indeed, the Skumanich law indicates that a star's rotation period will increase in accordance with the square root of its age. Since there is no specific requirement, however, for a star's convective turn-over time to change significantly during its main-sequence lifetime, it is expected that the Rossby number will increase as a star ages, and consequently any associated flare activity should decline. A common consensus on the rotation period for Proxima has not yet been established, but Benedict *et al.*[28] argue for a period of 83·5 days based upon photometric observations garnered with the *Hubble Space Telescope*'s (*HST*) fine-guidance sensor. In contrast, Guinan & Morgan[29] deduce a period of 31·5 ± 1·5 days from data obtained with the *International Ultraviolet Explorer* (*IUE*) satellite. Again, using *IUE* data, Doyle[30] has predicted, on the basis of an apparently good correlation between the activity index R_{HK} and Rossby number (derived for F8 to M4 dwarfs), that Proxima should have a rotation period of 51 ± 12 days. Using heuristic arguments, Reiners & Basri[31] have further suggested that Proxima's rotation period should fall between 17 and 25 days. While a wide range of possible rotation periods have been offered, Cincunegui, Díaz & Mauas[32] note that they all label Proxima as being a slow rotator in comparison to other M-dwarf stars, and this is in agreement with the idea that Proxima is an old star. Given that Proxima is indeed coeval with α Cen AB then it is likely that it has been spun down *via* some form of magnetic-braking mechanism. The surface magnetic-field strength of Proxima has been measured by Reiners & Basri[31], who find that $Bf = 600 \pm 150$ G, where f is the field filling factor. And, in addition, using the *Chandra X-ray Observatory* to search for an X-ray-emission halo, Wargelin & Drake[33] use a null detection to deduce an upper limit of 3×10^{-13} $M_\odot$/yr for Proxima's present mass-loss rate. The characteristic spin-down time for magnetic braking is usually taken to be of order $\tau_{\mathrm{brake}} = k^2(R_\star/R_{\mathrm{A}})^2(M_\star/\dot{M})$, where k^2 is the radius of gyration, $R_\star$, $M_\star$ and $\dot{M}$ are the radius, mass, and mass-loss rate of the star, and R_{A} is the Alfvén radius. For main sequence stars the k^2 term is typically of order 0·5, and adopting characteristic values of $(R_\star/R_{\mathrm{A}}) \sim 0{\cdot}1$, $M_\star \sim 0{\cdot}1 M_\odot$, and (say) $\dot{M} = 5 \times 10^{-14}$ $M_\odot$/yr, then $\tau_{\mathrm{brake}} \sim 10$ Ga. While the parameter values are admittedly uncertain (especially so in the case of the $\dot{M}$ and R_{A} terms), it appears that Proxima's age, assumed equal to that of α Cen AB, could well encompass a large fraction of its associated spin-down time-scale, and accordingly a slow rotation rate should not be too surprising — indeed, the spin-down time-scale estimate is close, as one might expect it to be, to the activity lifetime for M5 dwarf stars as determined by West *et al.*[21].

After the rotation period, the second term appearing in the Rossby number is that of the convective turn-over time. In general, this time-scale is evaluated as the integral over a star's convection zone with $\tau_{\mathrm{conv}} = \int dr/V_{\mathrm{c}}(r)$, where $V_{\mathrm{c}}(r)$ is the typical convective velocity at a distance r from the star's centre. Given Proxima's very low mass, it will be convectively unstable throughout its entire interior, and accordingly the integral relationship is approximated as $\tau_{\mathrm{conv}} \approx R_{\mathrm{PC}}/\langle V_{\mathrm{c}} \rangle$, where $\langle V_{\mathrm{c}} \rangle$ is the star-averaged convective velocity and R_{PC} is Proxima's radius. Appropriate to the mass of Proxima, D'Antona[34] provides data on the average convective velocity throughout the interior of a $0{\cdot}1$-$M_\odot$ stellar model (her Fig. 5). Two specific versions of the model have been computed and compared by D'Antona: one uses the standard mixing-length theory (MLT) of convection, while the other employs a full-spectrum-of-turbulence (FST) approach. Taking Proxima to be at least 2·5 Ga old (the limit of D'Antona's calculations) then the average internal convective velocities are $\langle V_{\mathrm{c}} \rangle \approx 7{\cdot}5$ m/s and 2 m/s for the FST and MLT models, respectively. Reassuringly, a three-dimensional, nonlinear, magnetohydrodamic simulation of a fully convective $0{\cdot}3$-$M_\odot$ star by Browning[35] yields typical convective velocities that are of order 12 m/s in the outer envelope and 2 m/s in the inner core. Accordingly, the convective turn-over time for Proxima is estimated to be $115 < \tau_{\mathrm{conv}}\,(\mathrm{days}) < 590$. With the rotational period of 83·5 days deduced by Benedict *et al.*[28], the expected Rossby number for Proxima is located in the range $0{\cdot}14 < \mathrm{R_o} < 0{\cdot}71$. If the 31·5-day rotation period from Guinan & Morgan[29] is applied, then the Rossby number falls in the range $0{\cdot}05 < \mathrm{R_o} < 0{\cdot}27$.

Odert *et al.*[36] have recently reviewed the data relating to M-dwarf stars in the solar neighbourhood with the intention of gauging the astrobiological implications for planets in orbit about active flare stars. Of interest to us here, however, are the summary data that they present concerning the relationships between the X-ray luminosity, the rotation period, and Rossby number. Guedel *et al.*[37] provide *XMM–Newton* satellite data on Proxima and find that the X-ray luminosity is L_X(quiescent) ~ 10^{20} W and $L_X/L_{bol} \sim 1{\cdot}5 \times 10^{-4}$. Comparing those numbers with the correlation diagrams provided by Odert *et al.*, it is found that the X-ray-luminosity data are consistent with a rotation period of 70 to 80 days and a Rossby number of order 0·2 to 0·3. Likewise, the data concerning the observed magnetic-field strength and Rossby number for M-dwarf stars presented by Reiners, Basri & Browning[38] (illustrated in their Fig. 6) are consistent with Proxima having a Rossby number of order 0·2. These combined results provide some confidence in the correctness of the 83·5-day period of rotation deduced by Benedict *et al.*[28]. In addition to this result, Gilliland[24] finds that a reasonably tight correlation exists between the activity index described by the ratio of the C IV line flux to the bolometric flux [$R = F_{C\,IV}/F_{bol}$] and the Rossby number (his Fig. 6). Linsky *et al.*[39] provide *IUE* flux data on the C IV line for Proxima, and accordingly, using an effective temperature of $T_{eff} = 3042$ K as deduced by Ségransan *et al.*[22] (which indicates a bolometric flux of $F_{bol} = 4{\cdot}85 \times 10^6\,W/m^2$ for Proxima), we find that $R_{C\,IV} = 3{\cdot}9 \times 10^{-6}$. This value of the activity index correlates with a Rossby number of order 0·25 in Gilliland's Fig. 6. Again, this is a result in good agreement with a slow ~580-day convective turn-over time-scale and the 83·5-day rotation period given by Benedict *et al.*[28]. It seems reasonable to conclude, therefore, that the slow rotation of Proxima is consistent with its being a relatively old, largely spun-down star. Indeed, while admitting to a broad range of uncertainty, Odert *et al.*[36] find some evidence that links the X-ray luminosity of M stars to their age, and with $L_X \sim 10^{20}$ W the implied age for Proxima is 5 ± 3 billion years — a result consistent with the isochrone and asteroseismic age estimates presented earlier.

Given that the observations reveal Proxima to be a slowly rotating star, with an age comparable to its (approximated) spin-down time-scale and its associated activity lifetime[21], it seems only reasonable to ask how it manages to support a surface magnetic field. To begin with, it is evident that Proxima's magnetic field cannot be any form of fossil remnant since the approximate magnetic diffusion time is very short, with $\tau_{mag} \sim R^2/\eta \approx 15$ years (assuming a turbulent magnetic diffusivity[35] $\eta = 2 \times 10^7$ m²/s and taking[15] $R = 0{\cdot}145\ R_\odot$). An active magnetic-field-generating mechanism must, therefore, be at play within Proxima — and herein resides yet another problem.

The standard αΩ dynamo model predicts that a strong correlation should exist between flare activity and rotation, with the activity of younger, more-rapidly-rotating stars being greater than that of older, more-slowly-rotating stars. This particular dynamo model is based upon the idea that over time a toroidal magnetic field is built-up at the tachocline, the high-rotational-shear boundary separating the radiative core from the convective envelope, *via* the action of differential rotation. While successful in accounting for the activity of Sun-like stars, the low stellar mass deduced for Proxima prohibits the αΩ dynamo from actually operating, the essential problem being that there is no tachocline region within Proxima's interior upon which to anchor a magnetic field. In consequence, it has been suggested that the α^2 dynamo model, in which a helicity is induced upon the convective motion by the Coriolis force, might be operating in low-mass, fully convective stars[35,40]. Even the α^2 dynamo mechanism must eventually fail, however, when a star's rotation period drops below some critical level, and this presumably accounts for the 7·0 ± 0·5 Ga activity lifetime for the M5 dwarf stars deduced by West *et al.*[21].

Unlike the αΩ dynamo, the α^2 dynamo is not expected to produce a modulation in the magnetic activity cycle, but, interestingly, there are some data that indicate Proxima does undergo a variation in its overall flare rate. Using photometric data obtained with the *HST Fine Guidance Sensor*, for example, Benedict *et al.*[28] report an 1100-day (~3·0-year) activity cycle for Proxima, while Cincunegui *et al.*[32] find a shorter 442-day (~1·2-year) activity modulation. The full observational situation is, once again, unclear at the present time and will only be resolved by the collection of more data. Matthews & Gilmore[41] nicely summarize the situation in which we find ourselves: "either the nearest star to the Sun is an extremely unusual flare star, or the incidence of flare activity in old stars has been considerably underestimated". Certainly present-day theoretical understanding is not wholly at odds with Proxima being an active flare star, but it is far from clear if it fits in to the normal scheme of things. In light of this situation it seems only reasonable to continue exploring alternative flare-producing mechanisms, and this brings us to the possibility that Proxima's activity might be enhanced, or even driven, by residual planetesimal accretion[42]. In this context, planetesimal is taken to mean structures analogous to the asteroids, cometary nuclei, and Kuiper Belt objects observed within our Solar System. The term residual is further used to signify that these putative impactors exist because planets have formed within the α Cen AB binary.

Planets in the α Centauri system

It has become abundantly clear during the past decade that planets are ubiquitous and that all low-mass stars can potentially support planetary systems of one form or another. Current statistics suggest[43] that of order 10% of Sun-like stars have attendant planets with masses in the range $0·3 < M/M_{\rm Jupiter} < 10$ with orbital periods between 2 and 2000 days. The percentage of stars supporting even-lower-mass, terrestrial planets may well be much higher than 10%, and some estimates suggest that as many as one Sun-like star in four could play host to Earth-sized worlds[44]. The observations further indicate that M-dwarf stars can support planetary assemblages[43], and it is not inconceivable, therefore, that all three of the stars in the α Centauri system harbour sub-Jupiter-mass and even terrestrial-mass worlds.

Benedict *et al.*[45] have used the *Fine Guidance Sensor* aboard the *Hubble Space Telescope* to perform an astrometric search for companions to Proxima and concluded that it does not host any planets with masses greater than $0·8\ M_{\rm Jupiter}$ having orbital periods in the interval $1 < P(\text{day}) < 10^3$. In addition, Kürster *et al.*[46] have made precise radial-velocity measurements of Proxima and argue that it has no planets in the mass range from 1·1 to 22 $M_{\rm Jupiter}$ with orbital periods between 0·75 and 3000 days. Endl & Kürster[47] further argue that if a terrestrial planet with a mass greater than 2 to 3 $M_\oplus$ existed within the habitability zone of Proxima (situated between 0·02 and 0·05 AU) then its presence should have been detected by now. Jovian planets beyond 2 AU, as well as closer-in Earth-mass planets may yet exist about Proxima, and, as noted by Kaltenegger[48], such planets might be directly searched for with the *James Webb Space Telescope* — once it is operational.

It is now reasonably well established that the probability of detecting an exoplanet increases in step with the iron abundance deduced for the parent star[49], and with respect to α Cen A and B Chmielewski *et al.*[50] find that they both have super-solar metallicities, with their [Fe/H] values being 0·22 and 0·26 respectively. Given these abundances, the probabilities of planetary companionship[49,51] are set at about 8% for α Cen A and 10% for α Cen B. Chmielewski *et al.* further report lithium abundances for both α Cen A and B, the log N(Li) values being $1·4 \pm 0·3$ and $< 0·4$, respectively, and Israelian *et al.*[52]

have recently argued (admittedly controversially since there is no obvious physical mechanism to explain the effect) that solar-type stars hosting planets are largely under-abundant in lithium when compared to planet-less Sun-like stars (which typically have log N(Li) > 1·5). Indeed, Israelian *et al.* comment that, "stars with high metallicity have a high probability of hosting planets. Those solar analogues with low Li content [low here meaning log N(Li) < 1·5] have an even higher probability of hosting planets". Given such possibilities, it would appear at face value that the odds of α Cen A and/or α Cen B hosting one or even more planets are encouragingly high, and we would echo the comments recently proffered by Guedes *et al.*[15], that, "a lack of planets orbiting these stars [that is, α Cen A and/or α Cen B] would thus provide a critical hint that there is a significant qualitative gap in our understanding of planet formation". We also note that the fact α Cen A and α Cen B form a relatively close binary system is not fatal to the idea of planet formation and the establishment of stable planetary orbits (as seen above — ref. 14). Indeed, of order 20% of the currently known exoplanets have been found in multiple-star systems[53,54].

Revisiting the impact flare hypotheses

Ejnar Hertzsprung[55] photographically recorded the very first flare star on the night of 1924 January 29, when a (now unidentified) star in Carina underwent a rapid and sudden change in brightness for about 1·5 hours. Hertzsprung suggested that a new type of nova might have been recorded, and commented that "a rough estimate indicates that a fall into the star of a body like a small planet would yield sufficient energy for an outburst as observed, but there may of course be other causes for the phenomenon". While Hertzsprung's "other causes" are certainly operating in the general case for flare stars[9], the impact hypothesis is not automatically ruled out as a contributing factor in systems such as that in which Proxima resides.

The impact hypothesis has been invoked on a number of occasions to explain various observational phenomena. Cowley[56] has suggested, for example, that a series of planetesimal impacts might offer a qualitative explanation for the abundance anomalies observed in upper-main-sequence chemically peculiar (CP) stars. And a planetary impact (or more correctly, cannibalism) hypothesis, similar to that invoked by Hertzsprung, has been considered by Retter[57] as a means of explaining the light-curve modulations recorded during the 2002 outburst of V838 Monocerotis. Andrews[42], however, has considered in great detail the flare–impact hypothesis, but limits the impactors to a size of just a few kilometres across. Indeed, Andrews notes that, "there may well be eras during a young star's life when cataclysmic bombardment by planetesimals becomes important", and indeed, we may look to the late heavy bombardment[58] within our own Solar System as a time when this statement most certainly held true. Here, in contrast, we are interested in reviewing the possibility that the impact hypothesis might have some application in the later stages of a star's life.

The essential mechanism at play in the impact hypothesis is that of kinetic-energy transfer. If, say, just 0·1% of its kinetic energy is imparted explosively to the surrounding stellar envelope then a 10-km-diameter asteroid can deliver some 2×10^{23} J of energy to a star such as Proxima Centauri (taking the impact velocity to be ~550 km/s — see below) during an accretion event. This transient burst of energy, possibly appearing as a 'spike' flare[12,35], would make for a significant short-term contribution to Proxima's overall energy budget — indeed, since $L_{PC} \approx 1{\cdot}5 \times 10^{-3}\ L_{\odot} \approx 6 \times 10^{23}$ J/s (see Table II), our putative 10-km impactor might produce over several seconds a 10 to 30%

increase in Proxima's luminosity. Not only can a large quantity of energy be transferred during an impact, but according to the composition of the impactor a significant number of free electrons might also be injected into a star's lower chromosphere. Indeed, following Andrews[42], we might expect a vapour cloud composed of ionized non-volatile material to push into the lower atmospheric layers during the end-phase of the impact. If we consider a composition similar to that of a carbonaceous-chondrite meteorite, with a density of 2000 kg/m^3, a cosmic iron abundance of 0·1% by mass fraction dictates that a 10-km-diameter asteroid will contain of order 10^{12} kg of iron — or about 10^{37} iron atoms. All of these iron atoms could be ionized to Fe VI, thereby liberating five electrons each, for a total energy budget of about 10^{20} J — which is about 0·1% of the explosive energy assumed to be liberated during the impact. The numbers, as such, are intended to be purely representative, rather than exact and/or compelling, but they are suggestive of the possibility that a 10-km diameter, carbonaceous-chondrite asteroid might reasonably place of order 10^{38} to 10^{39} electrons into the lower chromosphere of star during an impact — and this is the order-of-magnitude number of electrons involved in a typical solar/stellar flare[12,59]: here we take the electron number density to be 10^{17} m^{-3} and the volume of the flare region as 10^{22} m^3, corresponding to a magnetic loop of height 10^8 m with a footprint radius of 5×10^6 m — see Table 13 of ref. 9. Size for size, it is likely that a cometary impactor would yield fewer free electrons than a carbonaceous-chondrite asteroid, while an iron-rich M-type asteroid (with a 95% iron mass fraction) might yield orders of magnitude more.

A cometary cloud about α Cen AB

Hills[60] has considered in some considerable detail the dynamical properties of Oort Cloud-like structures and concludes that, "comet clouds similar to the Oort Cloud can be expected to be present about other stars having a massive planet like Jupiter and about binary stars". In Hills' scenario, the massive planet or binary companion is required to pump energy into the cometary nuclei and thereby place them into halo orbits. Hills further notes that triple-star systems might also support Oort Cloud-like structures (irrespective of any planets having formed), and argues that as a result of gravitational interactions a strongly bound central binary will form, composed of the two most massive stars, and that energy will be pumped into the lower-mass component until it is either ejected from the system or evolves to occupy a stable orbit with a large semi-major axis. Furthermore, Hills finds that the sizes of cometary clouds should be similar, irrespective of the mass of the central star(s), with an outer radius set at about 10^5 AU by the gravitational tidal field of the galaxy, and an inner radius, where the number density of cometary planetesimals peaks, situated at about 20 000 AU. Hills' inner radius is not a physical limit as such, but defines a region where the cometary orbits are relatively stable against the gravitational perturbations caused by the close passage of other stars. In our Solar System, for example, the cometary nuclei in Hills' sphere region are too small to be detected directly and they are only rarely perturbed into the inner regions where they can be observed while active[61]. In addition, Hills' inner sphere boundary is also the region beyond which the orbital inclination distribution begins to change from that corresponding to a disc-like structure to that of an isotropic one[61–63]. In the Solar System this corresponds to the region where the Kuiper Belt merges into the inner Oort Cloud.

In light of the analysis presented by Hills[60] it is entirely possible that the α Centauri system has an associated cometary cloud, whether, in fact planets

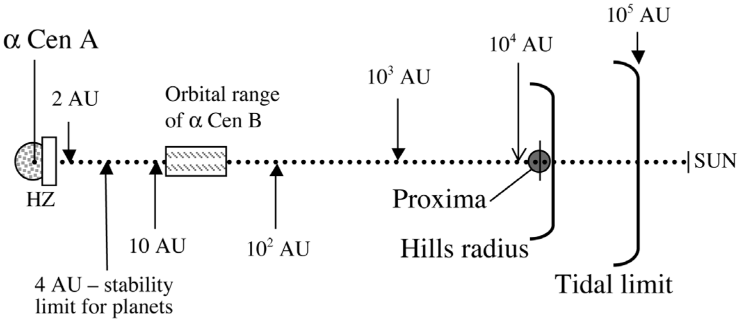

FIG. 2

A schematic log-scale diagram for the α Cen AB and Proxima system. The range for stable planetary orbits is from ref. 14, and the possible habitable planetary zone (HZ) is situated between 0·7 and 1·25 AU. The variable distance to α Cen B is based upon the data in Table I. Proxima Centauri is situated towards the inner edge of the putative cometary Hills sphere at 2×10^4 AU from α Cen A. The tidal limit at 10^5 AU is set according to the gravitational field of the Galaxy. The Sun-to-α Cen A distance is $2{\cdot}8 \times 10^5$ AU.

have formed there or not; and furthermore with its present separation Proxima is located close to Hills' sphere region where the greatest number of cometary nuclei are expected to reside (Fig. 2). The typical encounter time between planetesimal accretion events τ_{enc} can be estimated from the number density ρ of planetesimals at the orbital separation of Proxima, the relative velocity v_{rel} of Proxima with respect to the planetesimal cloud, and the total cross-section area σ_T from which Proxima might sample planetesimals: accordingly, $\tau_{enc} = 1/\rho\sigma_T\, v_{rel}$. Including the effect of gravitational focussing, the total cross-section for accretion is given by $\sigma_T = \pi R_{PC}^2[1 + v_{esc}^2/v_{rel}^2]$, where v_{esc} is the escape velocity for Proxima, and R_{PC} is Proxima's radius. The data presented in Table II can be combined to yield an escape velocity of $v_{esc} = 568 \pm 35$ km/s. Kokubo & Ida[64] further describe a means by which the relative velocity of the impacting planetesimal can be determined and argue that $v_{rel} = 2(R_H/a)v_{Kep}$, where R_H is the Hills radius $R_H = (M_{PC}/3M_{AB})^{1/3}a$, a is the separation of Proxima from α Cen AB, and v_{Kep} is the Keplerian velocity at separation a. Here it is assumed that Proxima has a near-circular orbit[10,13], can accrete from a region given by the Hills radius and that the relative-velocity estimate corresponds to that of a minimum value. Substitution of appropriate numbers reveals that: $\sigma_T = 2{\cdot}6 \times 10^{23}$ m^2, $v_{rel} = 0{\cdot}2$ km/s, and τ_{enc} (yr) $= 49{\cdot}2/\rho$, where the number density of planetesimals is now expressed in number per AU cubed.

In order to estimate the planetesimal number density we proceed by analogy with our own Oort Cloud[60,63]. If we take the inner Oort Cloud to extend from 2000–20 000 AU, we obtain a characteristic volume of order 10^{13} cubic AU, and if we further assume that the cloud contains of order 10^{12} cometary nuclei, then we obtain $\rho \sim 0{\cdot}1$ AU^{-3}. Given a reasonable range of possible cloud radii and planetesimal inventories, we would suggest that $0{\cdot}01 < \rho$ (AU^{-3}) < 1 is perhaps not unreasonable for a putative α Cen AB cometary cloud. This number density of cometary nuclei indicates that Proxima might suffer a planetesimal strike once every 50 to 5 000 years. Of course, one could easily juggle the numbers to obtain a strike rate that is as high as once per decade or even half-decade, but this, outside of any detailed constraints, is hardly satisfactory. It is noted, however, that a planetesimal number density of order 15–20 AU^{-3}, a large but not wholly unbelievable number, might be responsible for modulating Proxima's activity cycle. Indeed, it is possible that a significant number of icy planetesimals might have been captured by α Cen AB from the proto-planetary discs of other stars situated within its natal cloud. Levison *et al.*[66] have investigated this particular scenario with respect to the Sun and argue that perhaps 90% of Oort Cloud cometary nuclei were captured in this fashion. In addition, Ida *et al.*[66] have considered the consequences of very close encounters between newly formed stars and embryonic planetary systems in their natal cluster, and argue that such encounters could have very important consequences with respect to enhancing the velocity dispersion of first-formed planetesimals. Such an increase, they argue, would result in the onset of more disruptive encounters, thereby halting the planet-building process, and scattering numerous planetesimals and their collisional fragments into the outer disc regions — in this respect, Ida *et al.* suggest that much of the dynamical structure observed within the Kuiper Belt in our own Solar System is the result of a close, 100–200-AU pericentre, stellar encounter prior to the major outward migration phase of Neptune. The works by Levison *et al.*[65] and Ida *et al.*[66] along with the many recent observations of warped planet-forming discs[67], and the detection of cold-Jupiter exoplanets[68,69] having very large orbital semi-major axes, underscore the point that planets and cometary clouds form, more likely as a rule rather than an exception, under highly dynamic circumstances, and that these processes may well result in significant variations in the number density of nuclei contained within cometary-cloud structures.

Discussion and conclusions

In spite of being the closest multiple-star system to our Solar System, there is still much that has yet to be understood about α Centauri. The presence, or not, of attendant planets, and the true status of Proxima's trajectory are still open questions. We are perhaps on the threshold of being able to settle the first of these issues with the near-term deployment of the *James Webb Space Telescope*[48] (currently set for 2014), but the true form of Proxima's orbit may take considerably longer to resolve[9,10,13], requiring at the very least a precise determination for its current radial velocity. Indeed, at the present time it is unclear if α Cen AB and Proxima form part of a small kinematic group[70] or are the members (as argued for here) of a coeval triple system[9,41], or are simply a common-proper-motion pair (as first suggested by Innes[7] and Voûte[72] nearly a century ago), or, for that matter, are just happenstance close companions at the present epoch.

Harlow Shapley[73] first recorded the fact that Proxima is a flare star in 1951, at which time he commented, "dwarf red flare stars may become of considerable importance in considerations of stellar evolution". In this speculation he was entirely correct, and while he noted that the energies associated with Proxima's flares were comparable to those observed in solar flares, a linkage with magnetic activity was not directly made. Indeed, the ever-imaginative Fritz Zwicky[74,75] invoked in 1958 the existence of unstable nuclear matter, objects he prosaically called "nuclear goblins", to explain supernovae and the eruptive phenomenon observed in flare stars. In many ways, Zwicky's goblins act like an inverse-accretion event, in that the goblin nuggets only became unstable after ascending towards the surface of a star — the pressure within the star's interior otherwise being sufficient to keep them from becoming unstable and exploding. Interestingly, Zwicky suggested that the goblins had "a mass of about 5×10^{22} grams and a radius of about 3 to 10 meters" — this mass is equivalent to that of a 300-km-diameter planetesimal (assuming a density of 3000 kg/m^3). While Zwicky's goblins turned out to be a theoretical pipe-dream, it seems clear that from the very outset the origins of dwarf-star flare activity have stimulated much theoretical work and resulted in some remarkable 'out of the box' thinking, and while the driving mechanism responsible for producing such activity on Proxima may well turn out to be quite straightforward, it has yet to be fully explained. At this stage, however, given our own Solar System's Oort Cloud as a guide, it appears that the accretion of residual planetesimals might at best be a factor in modulating, on a time-scale of order multiple years, Proxima's flare-activity cycle. It seems highly unlikely that Proxima's overall flare activity is driven by accretion-impact events unless, that is, the number density of cometary nuclei, in any associated cometary cloud, is of order 10^{4-5} times greater than that estimated for the Hills sphere within the Solar System. Accordingly, the primary mechanism at play in producing flares on Proxima, in spite of its very slow rotation period, is most probably that of surface magnetic-field entanglement[12,35].

In this review an approximate analytic theory has been developed to explore the possibility that Proxima's flare activity might be driven and/or modulated by impact accretion. In light of this simplified approach it is suggested that the next step should be to perform a detailed numerical analysis of the cometary cloud-formation sequence. Such calculations would be particularly useful with respect to quantifying the number density of cometary nuclei, as a function of distance from α Cen AB, and in determining what rôle Proxima might play in shaping the cloud's development and structure.

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SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 219: OMEGA ANDROMEDAE, HD 25768, HD 42994, AND HD 215977

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The four stars were among 118 that were drawn to the writer's attention by Suchkov in late 1999 as photometrically identified candidate double stars. Observational support for the candidature of the first three of the objects treated here was so marginal that at the conclusion of a major radial-velocity survey of the Suchkov stars their velocities could be presented only in the listing of "stars that showed no certain change". Continuing careful observations have, however, demonstrated the double-lined natures of their spectra, and although in each case the two spectra are always heavily blended together it is now possible to present plausible orbits. The periods are about 255, 1572, and 958 days, and all three orbits are of modest eccentricity. Both components of ω And are quite rapidly rotating: they have $v \sin i$ values of 48½ and 43 km s^{-1}. The fourth star, HD 215977, was found in the survey to exhibit a radial-velocity trace that was so asymmetrical as practically to guarantee duplicity, but it showed very little change during the initial two-year observing campaign. Continued observations have demonstrated that the system has an orbit of rather high eccentricity (0·6) and a period of 8·7 years.

Introduction

In 1999 Suchkov & McMaster[1] proposed that in the *Hipparcos Catalogue* there were hundreds, if not thousands, of F-type stars that were unrecognized binary systems with fairly equal components. They were flagged up by a criterion of 'over-luminosity', $\Delta M_{c_0} \geq 0^{m}\cdot5$, whereby their luminosities according to their *Hipparcos* parallaxes were more than half a magnitude brighter than those deduced (*via* the photometric quantity c_0) from *uvbyβ* photometry. The dispersion of ΔM_{c_0} among F stars that are within 25 pc and could with confidence be considered single is only $0^{m}\cdot15$, so an apparent over-luminosity of as much as $0^{m}\cdot5$ ought to be very significant. Upon request, Suchkov provided a list of some 100 bright northern-hemisphere examples of objects with $\Delta M_{c_0} > 0^{m}\cdot5$, and the writer measured the radial velocities of most of them repeatedly. Well over half the stars did turn out to be binaries[2], but a substantial minority did not, so it seemed as if duplicity must not be the only cause of apparent over-luminosity. More complete information on those matters is, of course, to be found in the cited papers[1,2], and a more extensive summary than the present one was given in the *Introduction* to Paper 182[3] of this series.

When the final results[2] of the writer's radial-velocity survey of the Suchkov stars were published, indications of duplicity had been seen in the objects that are the subject of the present paper, but for the first three of those objects they were so slight that "with acknowledged inconsistency"[2] the velocities were listed among those of the "stars that showed no certain change". Those objects are, therefore, among the most difficult to measure of any whose orbits have ever been presented by the writer. In that regard the palm must be awarded to ω And, the difficulty of whose observations is further exacerbated by the high rotational velocities of both components. They cause the 'dip' in radial-velocity traces — already intrinsically weak owing to the star's early spectral type — to be smeared out to several times the normal width; it has a central depression only about 3% of the continuum height. It has been possible to document the system as a binary only because it is so bright, allowing traces with very good S/N ratio to be obtained with the modest telescope available to the writer. The fourth star, HD 215977, did appear to have shown a slight change during the survey epoch, its asymmetrical radial-velocity dip widening slightly.

ω Andromedae (*HR 417, HD 8799*)

Omega Andromedae, to be found about 9° north-following the famous Nebula, is not among the most conspicuous stars in the constellation, but is comfortably brighter than fifth magnitude; photometry by a number of observers[4–7] has put it at $V = 4^{m}\cdot83$, $(B-V) = 0^{m}\cdot42$, $(U-B) = -0^{m}\cdot01$. Its spectrum was first classified F, as long ago as 1890, in the *Draper Catalogue*[8]; it was refined[9] to F5 in 1912, and the same type was entered into the *Henry Draper Catalogue*[10]. In the 'MK'[11] era, Miss Roman[12] classed ω And as F5 III, a type that was correctly quoted a little later by Herbig & Spalding[13] as F5 IV after Johnson & Morgan[14] had made a deliberate change to the luminosity classification of the F stars. Slettebak[15] called it F4 IV, but the *Bright Star Catalogue*[16] stayed with the F5 IV type. The luminosity class seems to have been continued to be regarded as IV without any regard for the star's actual spectrum at all, because the accurate parallax of $33\cdot75 \pm 0\cdot82$ arc-ms obtained by *Hipparcos* shows the absolute magnitude to be $+2^{m}\cdot58 \pm 0^{m}\cdot05$ — about three-quarters of a magnitude brighter than a main-sequence F4 or F5 star is supposed to be — although (A. P.) Cowley[17] gave a classification of F5 V and Abt[18] one of F4 V. The luminosity excess of three-quarters of a magnitude is not only accurately reflected in the value[2] of ΔM_{c_0} but is exactly explained by the duplicity of ω And, which is shown here to consist of two mutually similar stars.

The absolute magnitude that corresponds to the spectrum of the star had in fact been correctly assessed long before Suchkov called attention to its conflict with the parallax. Already in 1980 Philip & Egret[19] had deduced $M_V = 3^{m}\cdot29$ from *ubvyβ* photometry[20], and in the following year Hauck & Philip[21] added a result of $3^{m}\cdot52$ from Geneva photometry[22]. The latter authors juxtaposed those absolute magnitudes with ones derived from a calibration of the class-IV MK type and also with the then-available parallax[23] (which was only $0''\cdot024$); but the point that they were making was not so much the discordance as that the photometric parallaxes were large enough to qualify ω And for addition to the (then recently published) supplement[24] to the *Catalogue of Nearby Stars*[25].

The star is a visual binary. In 1881 Burnham[26] discovered, with the 12-inch Clark refractor at the Lick Observatory, a 12^{m} companion only about $2''$ away from the principal star. The Observatory was then still in course of construction, and the telescope had only just been installed there. It was second-hand — the objective lens, at least, had belonged to Henry Draper in 1876–79. The 12-inch must have been a wonderful telescope — not to mention the corresponding quality of the observer! — to reveal such a faint companion so close to a bright star. In fact in the original description[27] of the instruments of the Observatory, in the first volume of the *Lick Publications*, there is the assertion that "The objective is of the very finest quality". While still in the makers' hands, in 1875, the lens had enabled the younger Clark to discover the duplicity of ζ Sge, an unequal double star whose orbit, which is now known, has a semi-major axis of only $0''\cdot14$; and at Lick, Barnard was able to make out, however indistinctly, detail on the $1''$ disc of Jupiter's satellite Io[28]. The ω And double system took Burnham's discovery designation β 999, and features in the successive double-star catalogues of Burnham[29] and Aitken[30] as BDS 758 and ADS 1152. The system also includes, as components C and D, a $5''$ double star of combined magnitude about 10, some $2'$ distant from ω And; the CD sub-system is β 82, having first been noted[31] by Burnham when he was using his own 6-inch refractor in 1872. Burnham himself knew that it was only an optical companion, since it showed rapid rectilinear motion in relation to the bright star, exactly mirroring the latter's large proper motion of about $0''\cdot35$ annually.

Rotational velocities have been listed for ω And by a number of authors. Herbig & Spalding[13] and Slettebak[15] gave $v \sin i$ as 75 km s^{-1}, but Wilson[32] put the star in his 'rotation class 4', which he equated to $v \sin i$ values of 45–55 km s^{-1}. A number of 69·0 km s^{-1} listed by Simon & Landsman[33] from an unidentified source might represent their own arbitrary 'refinement' of the 69 given in the *Bright Star Catalogue*[16], though that begs the question as to where *that* number came from. Comparatively recently (2007), Yoon *et al.*[34] have also quoted a $v \sin i$ of 69 km s^{-1} but not given the source; they listed the star as an "A-quality calibrator for *NPOI* 80-m baseline" (*NPOI* being an optical interferometer) — but they might be expected to repent if they actually try it! De Medeiros & Mayor[35] listed a rotational velocity of $65\cdot9 \pm 6\cdot6$ km s^{-1} from two observations with the OHP *Coravel*, but their result must be very uncertain because the maximum scanning range of that instrument is only 120 km s^{-1}, so the cross-correlation 'dip' must extend well beyond the ends of the scan. Nordström *et al.*[36] listed a value of 50 km s^{-1}, based on three measurements with the same instrument.

The radial velocity of ω And was measured seven times in the course of the great Lick survey[37], made in the first quarter of the 20th Century, of all stars brighter than $5^{m}\cdot5$. The velocities, quoted only to integer kilometres, range from +8 to +13, and there is the terse comment, "Poor lines", indicating that the breadth of the spectral lines reduced the precision of measurement. Other radial velocities of ω And have been published by a number of authors[35,36,38–40]; they are all in much the same range and none of them is likely to be any more accurate than the Lick ones since the same difficulty has been encountered by them all.

Those sources report only small numbers of velocities (1 to 3) except in the case of Abt & Levy[40], who in the course of a specific search at KPNO to identify and enumerate binaries among stars of solar type took as many as 20 spectrograms of ω And and concluded in their paper that its velocity was constant. Some time ago, the writer was party to a pretty drastic criticism[41] of that paper: it was shown that, among the 25 new orbits that were put forward by Abt & Levy, no fewer than 22 were not supported by the data on which they were supposedly based, and in at least 19 of those cases the evidence did not even show that the stars were binaries at all. On the other hand, certain actual binaries were missed. Paper 129[42] of the series of papers that includes this present one gave an orbit for the conspicuously double-lined object HR 6985, about which Abt & Levy said it had a "probably variable velocity" but "We did not succeed in determining the period." Paper 148[43] put an orbit to HR 7955, whose double-lined nature is less obvious; Abt & Levy had explicitly concluded that it has a constant velocity and is a single star. Now ω And is another analogous case.

New radial velocities and orbit of ω And

All the observations of the star (as of the others treated below) have been made with the *Coravel* instrument at the coudé focus of the Cambridge 36-inch telescope. The cross-correlation dip was found, at the first observation, to be very wide and shallow, so the velocity that it gave was subject to considerable uncertainty. Five measurements were made before the results of the survey[2] that included ω And were published; they ranged from +9·9 to +16·5 km s^{-1}. In the tabulated results (Table 1 of the paper) the mean velocity is listed as +13·7 ± 1·3 km s^{-1}, and the rotational velocity is given as '47:'. The entry in the 'Status' column is '(C)'. A footnote explains that "The entry C (for Constant) . . . refers to the non-detection of radial-velocity variations"; the brackets round it in the case of ω And were intended to indicate uncertainty. Notes on individual stars in the text of the paper include the statement, "This bright star is troublesome to measure owing to its high rotational velocity. The dip in radial-velocity traces has appeared to vary in width sufficiently to suggest that the star is double-lined, but it is so shallow that we cannot assert duplicity with confidence."

After the paper was submitted, ω And was retained on the Cambridge programme and observed more intensively and with longer integration times to obtain traces with better *S*/*N* ratios in an effort to see what, if anything, was going on. At times there seemed to be a shallow extension of the dip at one end or the other of the radial-velocity trace, and it was found possible to model the observed dip as double-lined, with a small second component that was responsible for the extension. As time went on, the reality of the duplicity became quite convincing, and a periodicity of about 250 days was divined in the results*. The derived radial-velocity curves did not, however, exhibit satisfactory continuity across the conjunctions, and the reductions of certain traces tended to stray away from the parameters entered as preliminary 'elements' (positions, depths, and widths for the two dips) towards solutions with much more equal components. Finally, in 2008, after about 80 measurements had been made and ω And had still not been properly understood, traces were obtained near a node of the orbit at much further increased *S*/*N*, with integration times sometimes reaching an hour and photon counts 500–1000 times greater than are needed to get good velocities of normal single objects. They showed slight inflections part-way up the wings of the very wide and shallow dip profile, on both sides, creating a characteristic appearance of a deepening of the central part of the profile. The tripartite nature of the profile is caused by the overlapping of two nearly-equal components, which individually have the rather bowl-shaped profiles that are created by rotational broadening. The situation is well illustrated by Fig. 1, where the computer-assigned profiles of the two individual dips and their summation are superimposed on a trace observed near a node of the orbit. Although the difference between the rotational velocities of the two components is not large, it is enough to make a noticeable difference in the gradients near the two edges of the combined profile; that accounts for the fact that in the early traces, whose *S*/*N* ratios were not nearly so good, a shallow projection was recognized on only one side of the dip.

*At that point the Abt & Levy[40] velocities were tested for the 250-day period and seemed to show a very plausible 238-day variation, although it was statistically a bit short of the 5% significance level. They do not, however, show any relationship at all to the period that is now much more accurately known.

Recently, the whole set of Cambridge observations of ω And has been reviewed in a systematic way. All the traces having more than 200 000 photon counts per 'bin' (a bin represents a velocity range of about ⅔ of a kilometre per second) and being within one or other of two defined ranges of phase near the nodes of the orbit (there were 39 of them) were reduced with the dip parameters left 'free', and the results in terms of the areas and rotational velocities assigned to the individual dips were averaged. Then the whole *ensemble* of 156 traces was re-reduced with the dip parameters fixed at those mean values. That set of final results is laid out in Table I; the orbit is illustrated in Fig. 2, and the orbital elements are as follows:

P	$= 254{\cdot}85 \pm 0{\cdot}10$ days	$(T)_{11}$	$=$ MJD $54220{\cdot}5 \pm 2{\cdot}5$
γ	$= +15{\cdot}18 \pm 0{\cdot}12$ km s^{-1}	$a_1 \sin i$	$= 61{\cdot}6 \pm 0{\cdot}7$ Gm
K_1	$= 17{\cdot}78 \pm 0{\cdot}21$ km s^{-1}	$a_2 \sin i$	$= 65{\cdot}4 \pm 0{\cdot}8$ Gm
K_2	$= 18{\cdot}87 \pm 0{\cdot}21$ km s^{-1}	$f(m_1)$	$= 0{\cdot}144 \pm 0{\cdot}005\, M_\odot$
q	$= 1{\cdot}061 \pm 0{\cdot}018$ $(= m_1/m_2)$	$f(m_2)$	$= 0{\cdot}172 \pm 0{\cdot}006\, M_\odot$
e	$= 0{\cdot}147 \pm 0{\cdot}009$	$m_1 \sin^3 i$	$= 0{\cdot}649 \pm 0{\cdot}019\, M_\odot$
ω	$= 123 \pm 4$ degrees	$m_2 \sin^3 i$	$= 0{\cdot}612 \pm 0{\cdot}018\, M_\odot$

R.m.s. residual (unit weight) $= 1{\cdot}44$ km s^{-1}

The orbit whose elements are given above was selected from among a number of experimental solutions. First, an investigation was made of the relationship between the velocity residuals and the *S/N* ratio of the traces (the number of counts per bin). The traces were sorted into six ranges of counts (designated A–F in Table I), with break-points at 50, 100, 200, 300, and 400 thousand per bin; the category of each trace is noted in Table I and is reflected in the size of the corresponding symbol in Fig. 2. The numbers of traces in those six categories are respectively 6, 21, 58, 39, 5, and 14. (The other 13 traces making up the total of 156 are so exactly single-lined that they could not sensibly be 'split' to yield two separate velocities and are therefore not utilized in the orbit.) The writer was surprised that there was not more difference between

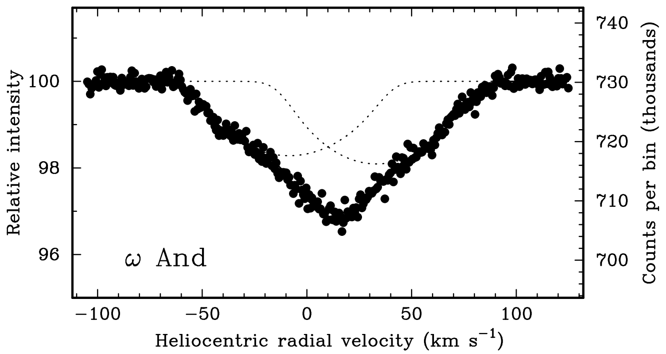

FIG. 1

Radial-velocity trace of ω Andromedae, obtained with the Cambridge *Coravel* on 2010 November 23. The dotted lines illustrate the computer's decomposition of the profile into the contributions of the two stars; in principle there is a full line showing the summation of the contributions, but it is entirely hidden by the points that it is intended to model.

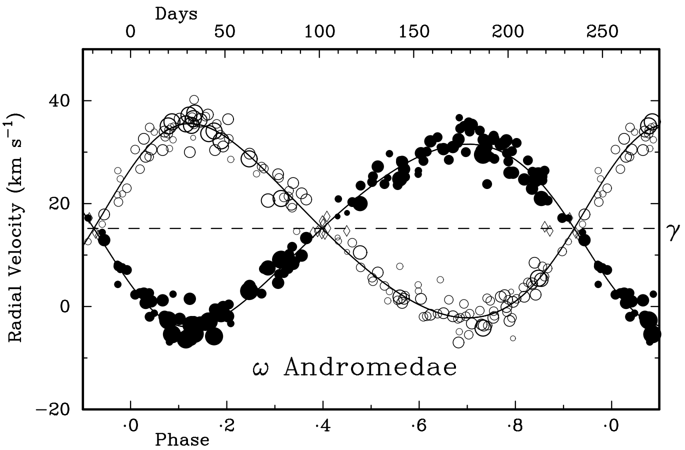

FIG. 2

The observed radial velocities of ω Andromedae plotted as a function of phase, with the velocity curves corresponding to the adopted orbital elements drawn through them. All the observations were made with the Cambridge *Coravel*. The filled circles represent radial velocities of the primary star (the one with the slightly wider dip and larger mass), while the open circles refer to the secondary. The different sizes of the symbols relate to the different levels of photon counts in the observations. There is surprisingly little difference in the residuals between traces having very different photon counts, but the velocities represented by the very largest symbols were found to deserve extra weight, and those plotted with the two smallest sizes of symbols were down-weighted. A few open diamonds plot velocities that were derived from single-lined reductions in cases where the blending of the two dips was very close; such observations were not included in the solution of the orbit.

the orbital residuals for the different categories. It seems that, although there would be no hope of disentangling the contributions of the two dips directly from poorly-integrated traces, passable velocities can nevertheless be wrung from them when the individual dip parameters are known and imposed upon the reductions. In the finally adopted orbit, whose elements are given above, the first two categories (counts <100K) were weighted ¼, and the rest ½ except for the 14 traces in the very best category (400K to more than a million), which were accorded unit weight. The two components were equally weighted in the solution and gave almost identical radial-velocity residuals.

It seemed a natural possibility that the velocities would be more accurately determined from traces obtained near the nodes of the orbit, when the velocity difference was greatest, than at other times when the blending was even more severe. The 39 nodal traces referred to above (just above the informal table) were segregated and attributed unit weight, thereby increasing the weights of the 28 of them that were not already in the best category from ½ to 1. The sum of squares of the residuals rose almost exactly in proportion to the total weight ascribed to the data set, a fact interpreted as showing (as indeed a naïve appraisal of Fig. 2 suggests) that the nodal traces are no better than any others of similar *S*/*N*.

In a third trial, the radial velocities originally determined from the individually independent reductions of the 39 nodal traces were substituted for those re-determined with the mean dip parameters imposed on them. The result was then decisively *worse*! Although of course the individual *traces* are always fitted best when the dip parameters are left free, it certainly turned out that, even in

TABLE I

Cambridge radial-velocity observations of ω Andromedae

'Category' indicates the S/N ratio of the trace in terms of the number of photon counts per bin. Categories A to F have photon counts of < 50, 50, 100, 200, 300, and 400 thousand, respectively.

Date (UT)	*Category*	*MJD*	*Velocity* *Prim.* $km\ s^{-1}$	*Velocity* *Sec.* $km\ s^{-1}$	*Phase*	*(O–C)* *Prim.* $km\ s^{-1}$	*(O–C)* *Sec.* $km\ s^{-1}$
1999 Dec. 19·88	A	51531·88	+18·2	+10·6	0·450	−1·3	+0·1
2000 Jan. 15·75	C	51558·75	+23·6	+1·2	0·555	−3·3	−1·5
Nov. 13·06	C	861·06	+23·8	+1·6	1·742	−7·3	+3·3
2001 Jan. 27·85	C	51936·85	−2·0	+34·8	2·039	−1·8	+3·3
Oct. 12·13	B	52194·13	−1·3	+33·9	3·049	−0·3	+1·6
2002 July 4·07	A	52459·07	−4·9	+35·2	4·088	−1·5	+0·3
14·11	C	469·11	−6·6	+36·8	·128	−2·6	+1·3
15·11	C	470·11	−2·8	+40·2	·131	+1·2	+4·7
21·12	C	476·12	−3·8	+36·9	·155	−0·3	+1·9
27·13	C	482·13	−0·4	+35·5	·179	+2·2	+1·5
Aug. 2·14	D	488·14	−1·9	+36·4	·202	−0·6	+3·7
21·17	C	507·17	+7·3	+26·8	·277	+2·9	+0·2
29·18	C	515·18	+6·3	+25·0	·308	−0·9	+1·3
Sept. 3·17	C	520·17	+7·3	+21·4	·328	−1·6	−0·4
5·12	C	522·12	+11·6	+19·2	·336	+2·0	−1·9
10·20	D	527·20	+9·9	+22·0	·355	−1·5	+2·8
23·98		540·98	+15·2		·410	—	—
Oct. 4·10		551·10	+14·7		·449	—	—
18·04	C	565·04	+25·3	+4·9	·504	+1·7	−1·3
Nov. 4·06	C	582·06	+25·2	+2·1	·571	−2·5	+0·3
11·01	B	589·01	+25·7	+4·2	·598	−3·4	+3·8
Dec. 17·91	C	625·91	+31·0	−3·7	·743	−0·1	−2·0
2003 Jan. 5·82	C	52644·82	+24·8	+3·7	4·817	−2·5	+1·4
15·92	C	654·92	+24·5	+7·8	·857	+0·8	+1·6
Feb. 14·84	C	684·84	+7·8	+20·3	·974	+0·1	−2·8
Mar. 15·80	B	713·80	+2·4	+32·4	5·088	+5·8	−2·5
June 11·09	A	801·09	+17·5	+13·4	·430	−0·4	+1·1
July 14·10	B	834·10	+28·5	+7·8	·560	+1·4	+5·3
Aug. 3·13	C	854·13	+32·9	−1·4	·638	+2·3	−0·2
9·12	C	860·12	+28·5	+1·3	·662	−2·7	+3·1
15·16	C	866·16	+34·6	−2·2	·686	+3·1	−0·1
17·15	C	868·15	+35·1	+0·5	·693	+3·6	+2·7
20·16	C	871·16	+34·0	−1·4	·705	+2·5	+0·8
31·10	C	882·10	+29·1	+1·1	·748	−1·8	+2·6
Sept. 14·10	C	896·10	+31·8	+1·5	·803	+3·4	+0·3
20·07	C	902·07	+28·4	+4·7	·826	+1·8	+1·6
29·04		911·04	+15·5		·862	—	—
Oct. 19·04	B	931·04	+14·4	+16·0	·940	+1·7	−1·8
Nov. 12·97	C	955·97	+2·6	+29·1	6·038	+2·7	−2·2
Dec. 5·93	C	978·93	−6·1	+35·7	·128	−2·1	+0·2
17·92	D	990·92	−0·6	+30·4	·175	+2·1	−3·8
2004 Jan. 8·95	B	53012·95	+2·9	+25·8	6·262	−0·2	−2·2
Feb. 28·77	C	063·77	+20·3	+12·4	·461	−0·1	+2·8
Aug. 17·16	A	234·16	−3·2	+32·8	7·130	+0·8	−2·7
Sept. 2·08	D	250·08	−0·1	+31·1	·192	+1·8	−2·2
5·09	C	253·09	+0·4	+32·6	·204	+1·6	+0·1
16·12	D	264·12	+4·0	+29·7	·247	+2·1	+0·4
Oct. 7·07	C	285·07	+10·2	+22·5	·329	+1·2	+0·8
26·06		304·06	+14·1		·404	—	—
Nov. 14·00	C	323·00	+23·5	+7·6	·478	+1·8	−0·6

TABLE I (*continued*)

Date (UT)	*Category*	*MJD*	*Velocity* Prim. km s^{-1}	*Velocity* Sec. km s^{-1}	*Phase*	*(O–C)* Prim. km s^{-1}	*(O–C)* Sec. km s^{-1}
2005 Jan. 8·83	C	53378·83	+30·0	−1·9	7·697	−1·5	+0·3
Aug. 11·15	B	593·15	+29·7	+2·9	8·538	+3·8	−0·9
Sept. 7·13	B	620·13	+31·0	+5·2	·644	+0·3	+6·5
28·12	C	641·12	+34·2	−0·8	·726	+2·8	+1·2
29·07	D	642·07	+30·3	−3·5	·730	−1·0	−1·5
Oct. 26·03	C	669·03	+26·2	+4·1	·836	+0·5	+0·1
Nov. 14·08	B	688·08	+17·2	+12·6	·911	+0·3	−0·7
29·91	B	703·91	+4·3	+26·4	·973	−3·6	+3·5
2006 Jan. 28·80	B	53763·80	−3·3	+28·6	9·208	−2·4	−3·7
Mar. 4·78	B	798·78	+8·9	+14·6	·345	−1·6	−5·6
July 17·12		933·12	+14·7		·872	—	—
Sept. 8·12	B	986·12	−6·9	+30·7	10·080	−3·9	−3·8
Oct. 5·14	C	54013·14	−1·1	+33·4	·186	+1·1	−0·2
27·00	C	035·00	+2·5	+27·2	·272	−1·5	+0·1
Nov. 28·02		067·02	+14·2		·398	—	—
2007 Jan. 1·95	B	54101·95	+25·0	+1·1	10·535	−0·7	−3·0
20·89	C	120·89	+28·3	−2·0	·609	−1·2	−1·9
Aug. 10·15		322·15	+16·6		11·399	—	—
Sept. 12·07	C	355·07	+23·8	+4·0	·528	−1·4	−0·5
30·07	B	373·07	+26·4	+3·0	·599	−2·7	+2·6
Oct. 21·01	C	394·01	+31·8	−2·4	·681	+0·4	−0·3
Nov. 9·01	C	413·01	+33·2	−0·9	·755	+2·5	+0·4
16·02	C	420·02	+29·8	−1·1	·783	+0·2	−1·0
Dec. 5·97	C	439·97	+26·4	+5·8	·861	+3·2	−0·9
2008 Jan. 5·91	B	54470·91	+7·7	+21·9	11·982	+1·2	−2·4
Feb. 12·84	C	508·84	−5·2	+35·4	12·131	−1·2	−0·1
July 30·13	A	677·13	+25·7	+2·9	·792	−3·4	+2·5
31·10	A	678·10	+30·4	−6·2	·795	+1·6	−6·9
Aug. 30·16		708·16	+17·2		·913	—	—
Sept. 28·06	D	737·06	+2·5	+32·6	13·027	+1·4	+2·4
Oct. 2·04	D	741·04	+1·0	+30·5	·042	+1·5	−1·3
9·08	D	748·08	−2·0	+34·0	·070	+0·5	0·0
11·04	F	750·04	−2·7	+35·1	·078	+0·2	+0·7
13·00	F	752·00	−5·4	+35·9	·085	−2·1	+1·1
17·08	D	756·08	−2·4	+36·5	·101	+1·4	+1·2
22·03	F	761·03	−6·0	+37·2	·121	−2·0	+1·7
25·10	F	764·10	−5·3	+37·6	·133	−1·3	+2·1
28·06	E	767·06	−3·4	+36·2	·144	+0·4	+0·9
Nov. 1·06	D	771·06	−2·4	+37·3	·160	+0·9	+2·5
8·02	F	778·02	−1·3	+32·2	·188	+0·8	−1·3
22·95	F	792·95	+3·0	+28·7	·246	+1·2	−0·6
Dec. 2·97	E	802·97	+7·5	+20·6	·285	+2·4	−5·2
9·90	F	809·90	+9·1	+21·0	·313	+1·6	−2·3
26·94		826·94	+14·4		·379	—	—
2009 Jan. 20·83	E	54851·83	+20·0	+10·5	13·477	−1·7	+2·2
Feb. 10·86	E	872·86	+24·8	+1·9	·560	−2·3	−0·6
Aug. 20·16	D	55063·16	+4·6	+25·7	14·306	−2·4	+1·8
28·16	D	071·16	+8·3	+24·0	·338	−1·5	+3·1
Sept. 4·10	D	078·10	+13·3	+20·8	·365	+1·0	+2·5
10·14		084·14	+14·6		·389	—	—
13·11		087·11	+16·0		·400	—	—
15·08		089·08	+17·5		·408	—	—
21·11	B	095·11	+20·9	+12·7	·432	+2·8	+0·6

TABLE I (*concluded*)

Date (UT)			*Category*	*MJD*	*Velocity*		*Phase*	*(O – C)*	
					Prim. *km s*$^{-1}$	*Sec.* *km s*$^{-1}$		*Prim.* *km s*$^{-1}$	*Sec.* *km s*$^{-1}$
2009	Oct.	9·06	C	54113·06	+24·2	+5·6	14·502	+0·7	−0·8
		12·03	D	116·03	+27·2	+6·6	·514	+2·9	+1·1
		25·01	D	129·01	+28·1	+0·7	·565	+0·7	−1·5
		26·02	D	130·02	+26·7	+1·5	·569	−0·9	−0·5
	Nov.	3·95	D	138·95	+29·8	+1·5	·604	+0·5	+1·3
		7·00	C	142·00	+30·1	−1·9	·616	+0·3	−1·6
		8·97	D	143·97	+32·1	−1·6	·623	+2·0	−1·0
		15·91	D	150·91	+30·6	−1·3	·651	−0·3	+0·2
		20·91	D	155·91	+31·0	−1·9	·670	−0·3	0·0
		23·90	D	158·90	+32·5	−7·0	·682	+1·0	−4·9
		30·93	D	165·93	+35·3	−3·3	·710	+3·8	−1·1
	Dec.	6·88	F	171·88	+29·5	−4·2	·733	−1·8	−2·3
		12·91	C	177·91	+28·7	−1·8	·757	−2·0	−0·5
		20·90	D	185·90	+26·0	−2·8	·788	−3·3	−3·0
		22·83	D	187·83	+26·0	+0·9	·796	−2·8	+0·2
		28·76	D	193·76	+24·7	+1·9	·819	−2·5	−0·5
2010	Jan.	1·87	D	55197·87	+22·9	+4·5	14·835	−2·9	+0·6
		3·83	D	199·83	+24·4	+2·3	·843	−0·7	−2·3
		6·82	E	202·82	+21·0	+5·2	·854	−2·9	−0·7
		17·90	C	213·90	+17·2	+10·7	·898	−1·5	−0·8
		26·74		222·74	+13·8		·933	—	—
		29·73	D	225·73	+12·9	+17·9	·944	+0·8	−0·6
	Feb.	5·76	B	232·76	+8·2	+21·7	·972	+0·2	−1·1
		10·78	C	237·78	+7·1	+23·0	·992	+1·8	−2·7
		17·76	C	244·76	+2·6	+26·7	15·019	+0·7	−2·6
		20·76	D	247·76	+0·7	+29·1	·031	+0·1	−1·5
	Mar.	1·77	D	256·77	+1·2	+30·4	·066	+3·5	−3·3
		4·77	C	259·77	−2·2	+33·6	·078	+0·7	−0·8
	Aug.	6·15	B	414·15	+36·7	−4·9	·684	+5·2	−2·8
		11·15	C	419·15	+35·8	−5·5	·703	+4·3	−3·3
		19·08	D	427·08	+32·4	−3·7	·734	+1·2	−1·8
		24·17	D	432·17	+32·6	−2·2	·754	+1·9	−0·9
		28·16	D	436·16	+31·5	+1·9	·770	+1·3	+2·6
		30·16	D	438·16	+31·9	+2·2	·778	+2·1	+2·5
		31·13	D	439·13	+32·3	−0·1	·782	+2·7	0·0
	Sept.	1·16	C	440·16	+28·2	+1·3	·786	−1·2	+1·2
		3·10	C	442·10	+30·2	−2·2	·793	+1·2	−2·7
		15·07	D	454·07	+24·6	+8·5	·840	−0·7	+4·1
		17·10	F	456·10	+25·3	+5·5	·848	+0·8	+0·3
		22·04	C	461·04	+20·6	+7·4	·868	−1·8	−0·1
	Oct.	7·05		476·05	+14·3		·927	—	—
		20·11	B	489·11	+7·2	+24·8	·978	0·0	+1·2
		28·00	C	497·00	+2·3	+30·5	16·009	−0·8	+2·5
	Nov.	12·98	C	512·98	−2·6	+33·0	·071	0·0	−1·0
		14·92	C	514·92	−2·2	+34·3	·079	+0·8	−0·2
		15·94	B	515·94	−4·1	+34·9	·083	−0·9	+0·2
		23·93	F	523·93	−6·4	+35·5	·114	−2·4	0·0
		26·02	D	526·02	+1·5	+30·0	·123	+5·5	−5·5
		26·92	F	526·92	−3·6	+35·2	·126	+0·4	−0·3
		27·95	F	527·95	−3·9	+36·5	·130	+0·1	+1·0
	Dec.	6·04	F	536·04	−2·9	+33·6	·162	+0·4	−1·2
		8·88	F	538·88	−5·8	+34·1	·173	−3·0	−0·2
2011	Jan.	14·90	C	55575·90	+6·5	+21·2	16·318	−1·6	−1·5
		18·89	D	579·89	+8·8	+19·8	·334	−0·7	−1·4

the cases of the 39 well-integrated and best-resolved traces referred to above, the mean *orbital residuals* were smaller when the orbit was computed from the velocities determined with the mean dip parameters imposed. There must, however, be a degree of optimism in the standard errors of the elements of an orbit determined in that way, particularly in respect of the velocity amplitudes, which could be affected systematically by any errors in the adopted dip parameters. The same must be true of all double-lined orbits in which all, or a significant fraction of, the traces have had the dip parameters imposed. In the more usual cases, however, the traces obtained near the nodes of the orbit are reduced 'free' and they are naturally the ones that have the most leverage in determining the amplitudes.

The adopted $v \sin i$ values for the two components are 48½ and 43 km s^{-1}, and are thought to be accurate almost to 1 km s^{-1}; their formal standard errors as the means from the 39 traces reduced 'free' are only about half that. The adopted ratio of dip areas is 1·07 to 1, the slightly wider dip being slightly the stronger, though the uncertainty in that ratio might just about admit of its being exactly unity. It is very tempting to imagine that the star with the slightly wider dip has a correspondingly slightly larger radius (and thus luminosity) than its companion, but a moment's reflection reminds us that the implicit assumption behind that meretricious idea — equal rotational periods — is altogether baseless: the rotational periods are about 1 day and can in no wise be synchronized.

According to a 'rule of thumb' that was devised in the investigation[2] of the Suchkov stars, the 1·07 dip ratio implies a difference of about $0^{\mathrm{m}}\!\cdot\!09$ in V magnitude, which would correspond to rather less than one sub-type in spectral type. The mass ratio is, however, distinctly different from unity, ascribing to the component with the wider dip a mass that is $6{\cdot}1 \pm 1{\cdot}8$ per cent larger than that of its companion, an amount that ought to correspond to a difference of about two sub-types. In view of the reservations that are admitted over both the dip ratio and the velocity amplitudes, we should perhaps be happy that the two methods agree as well as they do, both identifying the same component as the primary but indicating that the difference between the two is quite small. The best that one can say is that it is probably one or two sub-types, suggesting individual types close to F3 V and F5 V.

The orbital elements give values of $m_{1,2} \sin^3 i$ that are hardly half the masses normally ascribed to stars of those types, so the orbital inclination can be estimated as $\arcsin(\sqrt[3]{1/2})$, *viz.*, 52°. The sum of the projected orbital semi-axes is 127 Gm or 0·85 AU, suggesting that the angular separation of the components should at least sometimes be of the order of 0·85 times the parallax, or nearly $0''\!\cdot\!030$ — enough to be potentially resolvable with about a 4-m aperture and of course very easy with a separated-aperture interferometer, especially in view of the brightness of the system and the near-equality of its components. In fact, at the author's suggestion, ω And was observed in late 2008 with the CHARA[44] interferometer array at Mount Wilson and was reportedly resolved, but so far there does not appear to have been any systematic follow-up campaign.

HD 25768

HD 25768 is a 7½$^{\mathrm{m}}$ star in Taurus, about 4½° north-following the Pleiades. Its magnitude and colours have been given by Oja[45] as $V = 7^{\mathrm{m}}\!\cdot\!58$, $(B-V) = 0^{\mathrm{m}}\!\cdot\!50$, $(U-B) = -0^{\mathrm{m}}\!\cdot\!02$. There does not seem to be any spectral type available for it beyond the *HD* type[46] of F8. The *Hipparcos* parallax is $13{\cdot}97 \pm 1{\cdot}13$ arc-ms, indicating a distance modulus of $4^{\mathrm{m}}\!\cdot\!28 \pm 0^{\mathrm{m}}\!\cdot\!18$ and thus $M_V \sim 3^{\mathrm{m}}\!\cdot\!3$, before any allowance is made for interstellar absorption, which is probably small. The entry in the *Hipparcos Catalogue* is noted as an 'acceleration solution', implying that the apparent proper motion was irregular — normally an indication of duplicity. Nordström *et al.*[36] published for HD 25768 a radial velocity of −12·8 ± 0·8 km s^{-1}, from two *Coravel* observations, and a $v \sin i$ of 11 km s^{-1}. Apart from those basic data, the only interest in HD 25768 in the literature appears to have been as a 'check star' in three papers[47–49] on photometry of the 5^{m} Delta-Scuti star 44 (IM) Tau, a little over 1° following. In the second[48] of those papers, HD 25768 was said to be "slightly variable at a millimagnitude level", and a "preliminary frequency" of 0·88 cycles per day was suggested; in the third[49], it was referred to as a "former check star" and a photometric frequency of 0·885 cycles per day was confirmed, "which would be typical of Gamma Doradus stars found at these spectral types".

Radial velocities and orbit of HD 25768

The paper[2] giving the results of the radial-velocity survey of Suchkov's binary candidates included (in its Fig. 5) an illustration of two *Coravel* traces of HD 25768, which show dips of considerably different widths. They were in fact the first (widest) and the last (narrowest) among the five observations reported there. The radial velocities of the five (listed in Table 5 of the paper) showed a monotonic downward drift, but their whole range was only 1·1 km s^{-1} and by itself might not be seen as conclusive, although the change in dip profile certainly seemed significant.

The star was kept under observation, and in due course its dip profile widened again. Of course, once suspicions of its SB2 nature had been thoroughly aroused, the radial-velocity traces were integrated to much higher signal levels than before, as indeed is to be noticed in a comparison of the two published[2] traces. Traces (of which Fig. 3 is a particularly well-integrated example) obtained near the more favourable node of the orbit were sufficiently asymmetrical to allow the profiles of the (still heavily blended) dips to be modelled, and the agreement between the models of traces taken at different nodal passages was encouraging. The adopted dip parameters were a ratio of areas of 1 to 0·6 and projected rotational velocities of 6 and 0 km s^{-1}. Those parameters have been used for a

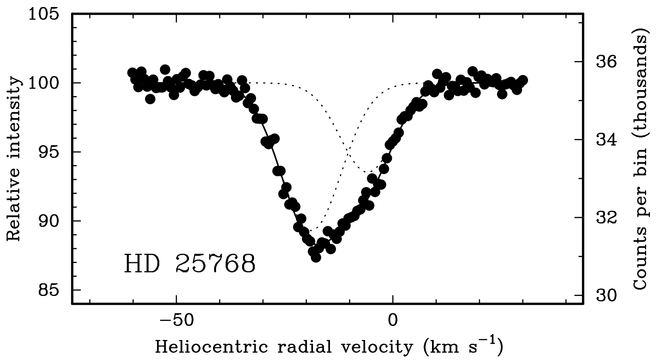

FIG. 3

Radial-velocity trace of HD 25768, obtained with the Cambridge *Coravel* on 2007 September 11, close to the orbital node at which the two components have the maximum separation in velocity.

systematic reduction of 48 of the available 54 traces; the other six, all taken near a conjunction early in the campaign, have been treated as single-lined and do not contribute to the orbit. The velocities are set out in Table II, and with the secondary's velocities weighted 0·3 to equalize the variances the orbit is found to have the elements noted below; it is illustrated in Fig. 4.

P =	1572 ± 4 days	$(T)_1$ =	MJD 52902 ± 7
γ =	−11·63 ± 0·04 km s^{-1}	$a_1 \sin i$ =	130·7 ± 1·3 Gm
K_1 =	6·32 ± 0·06 km s^{-1}	$a_2 \sin i$ =	132·8 ± 2·2 Gm
K_2 =	6·42 ± 0·10 km s^{-1}	$f(m_1)$ =	0·0361 ± 0·0011 $M_\odot$
q =	1·016 ± 0·019 (= m_1/m_2)	$f(m_2)$ =	0·0378 ± 0·0019 $M_\odot$
e =	0·290 ± 0·008	$m_1 \sin^3 i$ =	0·149 ± 0·006 $M_\odot$
ω =	248·4 ± 1·9 degrees	$m_2 \sin^3 i$ =	0·147 ± 0·004 $M_\odot$

R.m.s. residual (unit weight) = 0·27 km s^{-1}

The ratio of dip areas, expressed in stellar-magnitude terms, is $0^{m}\cdot55$, and by applying the factor of 1·15 proposed in the Suchkov paper[2] to find the difference in V magnitudes a ΔV of $0^{m}\cdot64$ is obtained. That corresponds to three spectral subtypes; a pairing of F7 V and G0 V would jointly produce colour indices very close to those observed. The tabular[50] absolute magnitudes for those types are $3^{m}\cdot8$ and $4^{m}\cdot4$, which when summed are equivalent to a single star of $M_V = 3^{m}\cdot3$, exactly the luminosity inferred from the parallax. Even the joint spectral type, which would be F8, is exactly as given in the *Henry Draper Catalogue*, so nearly everything falls into place with uncanny ease!

The one slightly discordant factor is the mass ratio. It agrees that the star that is obviously the primary (having much the larger dip signature in the radial-velocity traces) is slightly the more massive one, but is not as large as ought to correspond to the difference in types — it 'should' be more like 1·09 than 1·02. It has been indicated above, in the discussion on ω And, that, in cases such as

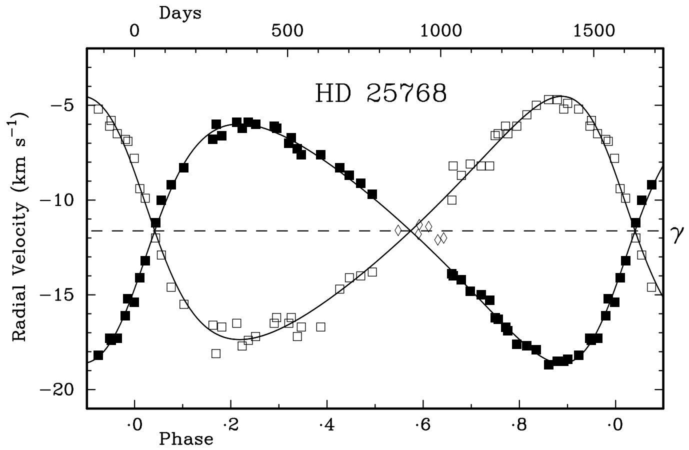

FIG. 4

The observed radial velocities of HD 25768 plotted as a function of phase, with the velocity curves corresponding to the adopted orbital elements drawn through them. As in the case of Fig. 2, filled symbols represent the primary star, open ones the secondary, and open diamonds plot single-lined reductions of observations that were not used in the solution of the orbit.

TABLE II

Cambridge radial-velocity observations of HD 25768

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
2000 Feb. 21·92	51595·92	−6·0	−18·1	0·169	+0·3	−1·0
Oct. 17·12	834·12	−7·0	−16·5	·320	−0·2	+0·1
Nov. 14·08	862·08	−7·3	−17·2	·338	−0·3	−0·9
2001 Jan. 29·86	51938·86	−7·6	−16·7	0·387	+0·2	−1·2
Oct. 10·08	52192·08	−11·6		·548	—	—
Dec. 14·96	257·96	−11·8		·590	—	—
18·01	261·01	−11·3		·592	—	—
2002 Jan. 17·89	52291·89	−11·4		0·612	—	—
Feb. 16·87	321·87	−12·1		·631	—	—
Mar. 7·85	340·85	−12·0		·643	—	—
Apr. 3·84	367·84	−13·9	−10·0	·660	−0·2	−0·5
Sept. 2·17	519·17	−16·3	−6·5	·756	0·0	+0·4
Oct. 4·13	551·13	−16·9	−6·5	·777	−0·1	−0·1
Nov. 2·11	580·11	−17·6	−6·1	·795	−0·4	−0·2
Dec. 5·04	613·04	−17·7	−5·5	·816	0·0	0·0
2003 Jan. 5·01	52644·01	−17·9	−5·0	0·836	+0·2	+0·1
Feb. 13·92	683·92	−18·7	−4·7	·861	−0·2	0·0
Mar. 14·85	712·85	−18·5	−4·7	·879	+0·1	−0·2
Apr. 4·83	733·83	−18·5	−5·2	·893	+0·1	−0·7
Aug. 20·13	871·13	−16·1	−6·8	·980	−0·2	+0·4
Sept. 18·13	900·13	−15·4	−7·8	·999	−0·7	+0·7
Oct. 24·12	936·12	−13·2	−9·9	1·021	−0·1	+0·3
Nov. 27·03	970·03	−11·2	−12·0	·043	+0·3	−0·2
Dec. 15·98	988·98	−10·0	−12·9	·055	+0·7	−0·3
2004 Jan. 16·96	53020·96	−9·2	−14·6	1·075	+0·2	−0·7
Feb. 27·89	062·89	−8·3	−15·5	·102	−0·2	−0·3
Sept. 5·14	253·14	−6·2	−17·7	·223	−0·2	−0·3
Oct. 19·16	297·16	−6·0	−17·2	·251	+0·1	+0·1
Dec. 19·05	358·05	−6·1	−16·5	·290	+0·3	+0·4
26·95	365·95	−6·2	−16·2	·295	+0·3	+0·7
2005 Feb. 12·85	53413·85	−6·7	−16·2	1·325	+0·1	+0·3
Mar. 17·86	446·86	−7·6	−16·7	·346	−0·5	−0·5
Aug. 22·13	604·13	−8·7	−14·1	·447	+0·2	+0·3
Sept. 28·18	641·18	−9·1	−14·0	·470	+0·3	−0·1
Nov. 5·10	679·10	−9·7	−13·8	·494	+0·2	−0·4
2006 Oct. 27·08	54035·08	−15·0	−8·2	1·721	+0·3	−0·3
Nov. 24·10	063·10	−15·3	−8·2	·739	+0·5	−0·8
Dec. 11·99	080·99	−16·2	−6·6	·750	−0·1	+0·5
2007 Jan. 14·91	54114·91	−16·7	−6·1	1·772	−0·1	+0·4
Aug. 6·11	318·11	−18·4	−4·9	·901	+0·2	−0·3
Sept. 11·15	354·15	−18·2	−5·2	·924	+0·1	−0·3
Oct. 18·11	391·11	−17·3	−6·1	·947	+0·3	−0·5
23·10	396·10	−17·4	−5·8	·950	+0·1	−0·1
Nov. 12·01	416·01	−17·3	−6·5	·963	−0·4	−0·2
Dec. 16·95	450·95	−15·2	−6·9	·985	+0·4	+0·7
2008 Jan. 24·87	54489·87	−14·1	−9·4	2·010	−0·2	−0·1
Sept. 20·17	729·17	−6·8	−16·6	·162	−0·4	+0·4
Oct. 19·12	758·12	−6·6	−16·7	·181	−0·5	+0·5
Dec. 7·04	807·04	−5·9	−16·5	·212	+0·1	+0·9

TABLE II (*concluded*)

Date (UT)			*MJD*	*Velocity*		*Phase*	*(O – C)*	
				Prim. *km s*$^{-1}$	*Sec.* *km s*$^{-1}$		*Prim.* *km s*$^{-1}$	*Sec.* *km s*$^{-1}$
2009	Jan.	13·98	54844·98	−5·9	−17·4	2·236	+0·1	−0·1
	Nov.	9·06	55144·06	−8·3	−14·7	·426	+0·2	+0·1
2010	Nov.	15·04	55515·04	−14·0	−8·2	2·662	−0·2	+1·2
	Dec.	11·99	541·99	−14·2	−8·7	·680	0·0	+0·3
2011	Jan.	9·90	55570·90	−14·8	−8·1	2·698	−0·1	+0·4

these where a set of adopted dip parameters is imposed on the reductions of all the radial-velocity traces, any error in those parameters could have a systematic effect on the derived velocity amplitudes. The sensitivity of that effect has been investigated by subjecting the trace shown here as Fig. 3 to experimental reductions with different dip parameters imposed. The experiments showed that the components' velocities were not very sensitive to small changes in the adopted $v \sin i$ values, but that a change in the imposed dip ratio from 0·6 to 0·55 was quite enough to change the velocities into agreement with the 'desired' mass ratio of 1·09. The ratio of 0·55 is by no means out of the question, and is in fact exactly the ratio that is found for that particular trace when it is reduced 'free'. It would obviously be possible to make a fresh set of reductions of the observations with that ratio imposed, and then everything would look perfect! — but the writer would not countenance such an artifice, preferring to leave the dip ratio as it was judged from the observed traces rather than revise it in the light of the q value that stems from their results. All the same, the source of the discrepancy seems clear, and the discrepancy itself does not seem serious since it could be removed completely by a small and acceptable change in the reductions of the original data. That change would suggest an increase in the ΔV to about $0^{m}\!\cdot\!7$, and would have negligible effects on the other conclusions already drawn above.

A binary system consisting of stars differing in brightness by $0^{m}\!\cdot\!64$, as proposed here for HD 25768, will have an integrated magnitude $0^{m}\!\cdot\!48$ brighter than the primary — which will go a good way towards explaining the ΔM_{c_0} anomaly of $0^{m}\!\cdot\!77$ listed by Griffin & Suchkov[2] for HD 25768. But in addition, there is another effect that operates in the same direction and is often at least comparable in magnitude — one that was overlooked by Suchkov & McMaster[1] in their original paper on the ΔM_{c_0} parameter as well as in the write-up[2] of the radial-velocity survey of the Suchkov stars*. The effect was drawn to attention in Paper 185[51] of this series, which includes a table showing that ΔM_{c_0} remains above $0^{m}\!\cdot\!5$ for pairs of stars with magnitude differences up to $1^{m}\!\cdot\!7$, although the actual excess luminosity at that ΔM is scarcely more than $0^{m}\!\cdot\!2$.

That second effect is as follows. Any luminosity assessment derived from spectral characteristics (such as, in particular, from *uvbyβ* photometry) may be expected to give a result more or less corresponding to the weighted-mean spectral type. In fact, the c_0 index that underlies the ΔM_{c_0} parameter is known[51] to run very close to linearly with absolute magnitude. In the present case that implies that (since a fraction $^{0\cdot6}/_{1\cdot6}$ of the light is supposed to come from the secondary star) the c_0 magnitude is expected to correspond to a star that is *that* fraction of $0^{m}\!\cdot\!64$, *viz.*, $0^{m}\!\cdot\!24$, fainter than the primary star. The difference

*If it had been taken into account, the residual ΔM_{c_0} values in the final column of Table 3 of that paper[2] would have been substantially reduced and improved in a number of instances.

between the photometric estimate and the real total luminosity of the binary is thus expected to be $0^{m}\cdot48 + 0^{m}\cdot24$, almost exactly reproducing the ΔM_{C_0} value[2] of $0^{m}\cdot77$.

The masses found from the orbital elements, where they are multiplied by the factor $\sin^3 i$, are about ⅛ of those to be expected for stars of their types, so $\sin i$ must be very close to ½ and thus $i \sim 30°$. The semi-major axis of the relative orbit, obtained by summing the values of $a_{1,2} \sin i$ and dividing by $\sin i$ which we have seen is ½, is about 520 Gm or 3½ AU. At the ~70-pc distance of HD 25768 it would subtend 0″·05 if seen normal to the line of sight, so the system might well be resolvable on occasion with telescopes of the sizes that have often been used for speckle interferometry.

HD 42994

HD 42994 is a 7^{m} star of HD type[46] F8, to be found about 4° north-following the bright ($3^{m}\cdot7$) star δ Aur, whose orbit was presented in a recent paper[52] in this series. There does not appear to be any ground-based *UBV* photometry nor any MK type available for it; the only information in the literature that it seems appropriate to record here is a single radial-velocity observation by Nordström *et al.*[36], which gave a result of $+9\cdot5 \pm 0\cdot7$ km s^{-1} and a $v \sin i$ of 12 km s^{-1}*. As far as photometry is concerned, *Tycho* comes to the rescue, with results that transform to $V = 7^{m}\cdot16$, $(B - V) = 0^{m}\cdot50$. The parallax of $16\cdot18 \pm 1\cdot08$ arc-ms, which came from an 'acceleration solution' that suggests that *Hipparcos* did notice the star's duplicity, puts the distance modulus at $3^{m}\cdot96 \pm 0^{m}\cdot15$, so the absolute magnitude of the HD 42994 system is close to $+3^{m}\cdot2$.

Unlike HD 25768, HD 42994 was already under careful observation as a probable SB2 system before the paper[2] by Griffin & Suchkov was submitted for publication. On that account more observations of it are listed there than there are for other stars that were not claimed outright as binaries, and many of them were integrated to good *S/N* ratios, as may be seen from the two traces published in that paper's Fig. 5. Those traces show mutually reversed asymmetries. A trace obtained at the favourable node in HD 42994's moderately eccentric orbit and integrated to a still much better *S/N* ratio than the one shown in that figure appears here in *this* paper's Fig. 5. Even at the other node, and *a fortiori* during the two-thirds of the orbit when the sign of the velocity difference is opposite to that in Fig. 5, the asymmetry of the dip profile is only very slight. That is indeed compellingly illustrated by the second trace in the earlier paper[2], which shows it (on 2002 January 1) almost at the node.

In some ways the case of HD 42994 is even more problematical than those of ω And and HD 25768, because in the case of HD 42994 one of the dips is quite wide and the other is always wholly superimposed upon it. Even very good traces, reduced with all the dip parameters free to take their optimal values, do not always agree well on what those parameters are. There is, however, general agreement that the major part of the dip is attributable to a component having a projected rotational velocity near 16 km s^{-1}; the parameters finally adopted are that the components have a dip ratio of two to one and $v \sin i$ values of 16 and 4 km s^{-1}. Altogether there are 77 radial-velocity observations; they are listed in Table III. Two of the earliest ones, which were not sufficiently integrated, and

*As in so many other instances, including those of ω And and HD 25768, the Nordström result is noted in the 'measurements' section of the *Simbad* bibliography but the Griffin & Suchkov[2] set of measurements (of which there are 13 for HD 42994) is not; analogous but worse discrimination (the complete omission of the writer's paper from bibliographies) has repeatedly been noted in this series of papers, most recently in the one[53] immediately previous to this.

TABLE III

Cambridge radial-velocity observations of HD 42994

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
2000 Feb. 21·99	51595·99	+11·4		0·569	—	—
Oct. 9·22	826·22	+9·7	+12·6	·809	−0·4	−0·1
Nov. 14·15	862·15	9·5	13·0	·847	+0·3	−0·6
20·13	868·13	11·0		·853	—	—
2001 Jan. 29·92	51938·92	5·9	16·6	0·927	−0·8	+0·4
Feb. 13·99	953·99	6·8	16·6	·943	+0·6	−0·1
Mar. 4·95	972·95	6·2	17·5	·962	+0·5	+0·4
May 11·87	52040·87	8·7	14·4	1·033	+1·1	−0·8
Aug. 2·13	123·13	11·8		·119	—	—
21·14	142·14	10·7		·139	—	—
Oct. 4·20	186·20	13·5	10·6	·185	+0·5	+0·9
Nov. 1·10	214·10	13·4	9·4	·214	+0·1	0·0
4·12	217·12	13·8	9·4	·217	+0·4	0·0
5·17	218·17	13·3	10·0	·218	−0·1	+0·7
2002 Jan. 1·04	52275·04	12·7	9·0	1·278	−1·0	0·0
Feb. 6·04	311·04	12·7	9·0	·315	−1·1	+0·1
Mar. 26·88	359·88	13·7	9·4	·366	−0·1	+0·5
Apr. 23·90	387·90	13·4	9·2	·396	−0·3	+0·2
Sept. 28·20	545·20	12·6	10·4	·560	−0·5	+0·8
Oct. 18·19	565·19	12·7	10·1	·581	−0·2	+0·3
Dec. 5·08	613·08	13·5	10·3	·631	+1·0	+0·1
2003 Jan. 5·10	52644·10	11·2		1·663	—	—
Feb. 15·01	685·01	11·4		·706	—	—
Mar. 15·93	713·93	11·2		·736	—	—
Apr. 7·86	736·86	11·1		·760	—	—
May 6·87	765·87	10·9		·790	—	—
Aug. 31·15	882·15	7·9	15·4	·911	+0·7	−0·2
Sept. 24·19	906·19	6·9	16·2	·936	+0·5	−0·3
Oct. 12·21	924·21	5·5	16·8	·955	−0·3	−0·2
27·14	939·14	5·8	17·3	·971	+0·2	+0·1
Nov. 28·08	971·08	6·1	16·5	2·004	−0·1	−0·2
Dec. 16·11	989·11	6·9	16·1	·023	−0·1	+0·3
2004 Jan. 17·10	53021·10	8·7	14·5	2·056	−0·3	+0·7
Feb. 23·02	058·02	11·6		·095	—	—
Mar. 29·91	093·91	11·3		·132	—	—
Apr. 21·88	116·88	12·2	10·4	·156	−0·4	+0·3
Oct. 7·21	285·21	14·1	8·4	·332	+0·3	−0·5
Dec. 27·10	366·10	14·0	8·2	·417	+0·3	−0·8
2005 Jan. 22·09	53392·09	13·1	8·6	2·444	−0·5	−0·5
Feb. 12·95	413·95	13·0	9·4	·466	−0·5	+0·2
Mar. 18·92	447·92	12·6	9·5	·502	−0·8	+0·2
Apr. 27·87	487·87	12·8	9·5	·544	−0·4	0·0
May 14·89	504·89	12·5	10·0	·561	−0·6	+0·3
Nov. 5·18	679·18	11·8		·743	—	—
Dec. 17·16	721·16	11·4		·787	—	—
2006 Feb. 8·99	53774·99	8·9	13·6	2·843	−0·4	+0·1
Mar. 3·94	797·94	7·9	14·6	·867	−0·7	+0·4
Apr. 10·89	835·89	7·1	15·1	·907	−0·3	−0·4
May 9·88	864·88	5·9	15·6	·937	−0·4	−0·9
Aug. 11·13	958·13	+7·8	+16·0	3·034	+0·1	+0·9
Sept. 30·20	54008·20	11·7		·087	—	—
Oct. 27·17	035·17	+11·4		·115	—	—

TABLE III (*concluded*)

Date (UT)	*MJD*	*Velocity*		*Phase*	*(O–C)*	
		Prim. *km s⁻¹*	*Sec.* *km s⁻¹*		*Prim.* *km s⁻¹*	*Sec.* *km s⁻¹*
2006 Nov. 24·13	54063·13	+13·1	+10·3	3·144	+0·8	−0·1
Dec. 17·08	086·08	13·4	9·7	·168	+0·6	−0·2
2007 Jan. 14·11	54114·11	12·7	9·9	3·197	−0·5	+0·4
Feb. 26·83	157·83	13·9	8·8	·243	+0·4	−0·4
Mar. 21·91	180·91	12·8	9·6	·267	−0·9	+0·5
Apr. 14·92	204·92	13·6	9·9	·292	−0·1	+0·9
May 18·87	238·87	13·4	9·2	·327	−0·4	+0·3
Oct. 21·20	394·20	13·8	9·1	·490	+0·4	−0·2
Nov. 16·19	420·19	13·0	8·7	·517	−0·3	−0·7
2008 Feb. 17·97	54513·97	12·2	10·1	3·615	−0·5	+0·1
Mar. 31·90	556·90	12·1	10·7	·659	−0·2	+0·3
Oct. 9·20	748·20	9·0	13·7	·859	+0·1	−0·2
Dec. 7·11	807·11	6·0	17·1	·921	−0·9	+1·2
2009 Jan. 3·05	54834·05	5·9	16·6	3·949	−0·1	−0·2
24·05	855·05	5·0	17·2	·971	−0·6	0·0
Mar. 5·96	895·96	6·0	16·4	4·013	−0·5	+0·1
20·94	910·94	7·7	15·5	·029	+0·3	+0·1
Apr. 7·89	928·89	8·8	14·3	·048	+0·3	0·0
24·86	945·86	9·5	13·2	·065	0·0	−0·1
Oct. 23·24	55127·24	15·4	8·6	·255	+1·8	−0·5
Dec. 20·08	185·08	13·9	8·1	·315	+0·1	−0·8
2010 Jan. 31·05	55227·05	13·8	8·4	4·359	0·0	−0·5
Feb. 26·97	253·97	14·1	8·8	·387	+0·3	−0·2
Apr. 8·88	294·88	13·9	9·0	·430	+0·2	0·0
Oct. 20·20	489·20	+13·6	+9·8	·632	+1·1	−0·4

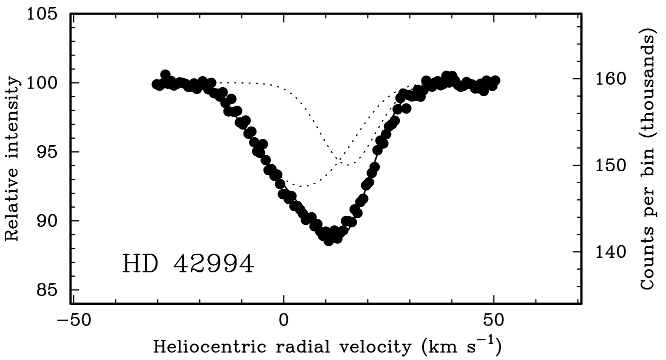

FIG. 5

Radial-velocity trace of HD 42994, obtained with the Cambridge *Coravel* on 2009 January 3, close to the node of the orbit.

13 others that were obtained when the twin velocities were almost identical and the dips are not reliably separable, have been treated as single-lined; the other 62 have been reduced with the adopted dip parameters uniformly imposed

upon them. They readily yield the orbit portrayed in Fig. 6. The residuals of the secondary proved to be somewhat smaller than those of the primary, so the latter's velocities have been weighted ⅔ in the final orbital solution. The unusual situation whereby it is the *primary*'s velocities that need to be down-weighted doubtless arises owing to the relatively great width and consequent shallower wing gradients of the primary dip. The orbital elements are as follows:

P	= 958·1 ± 1·5 days	$(T)_3$	= MJD 53925 ± 4
γ	= +11·37 ± 0·05 km s^{-1}	$a_1 \sin i$	= 48·0 ± 1·3 Gm
K_1	= 4·09 ± 0·10 km s^{-1}	$a_2 \sin i$	= 48·9 ± 1·1 Gm
K_2	= 4·16 ± 0·09 km s^{-1}	$f(m_1)$	= 0·0048 ± 0·0004 $M_\odot$
q	= 1·02 ± 0·03 (= m_1/m_2)	$f(m_2)$	= 0·0051 ± 0·0003 $M_\odot$
e	= 0·453 ± 0·016	$m_1 \sin^3 i$	= 0·0200 ± 0·0012 $M_\odot$
ω	= 205·3 ± 2·3 degrees	$m_2 \sin^3 i$	= 0·0196 ± 0·0013 $M_\odot$

R.m.s. residual (unit weight) = 0·45 km s^{-1}

The factor of two between the dip strengths is $0^{m}·75$ in magnitude terms, and according to the 'rule of thumb' noted above should correspond to a ΔV of about $0^{m}·85$. The combined magnitude of the pair should then be $0^{m}·41$ brighter than the primary on its own. The HD 42994 system can be neatly modelled by stars of types F6 V and G1 V, which[50] (by interpolation) have absolute magnitudes of $3^{m}·6$ and $4^{m}·5$ and colour indices of $0^{m}·45$ and $0^{m}·60$. Summation of the V and B magnitudes produces for the system as a whole $M_V = 3^{m}·21$ and $(B - V) = 0^{m}·49$, agreeing extremely closely with both the parallax-based luminosity and the observed colour index. Since, with $\Delta V \sim 0^{m}·85$, the secondary is considered to provide about 31% of the total light of the system, the photometrically estimated luminosity is expected to be that of a star that is 0·31 × $0^{m}·85$, *viz.*, $0^{m}·26$, fainter than the primary. Thus, in a discussion that parallels that made regarding HD 25768 above, we find that the difference between the photometric and parallactic luminosity estimates

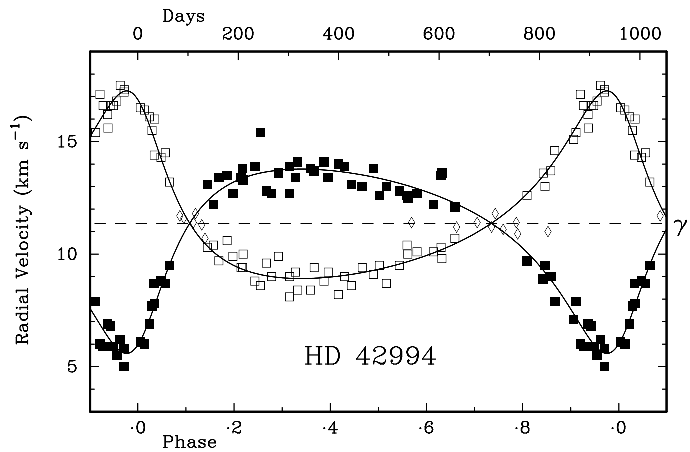

FIG. 6
As Fig. 4, but for HD 42994.

should be $0^{m}{\cdot}41 + 0^{m}{\cdot}26$, very largely explaining the ΔM_{C_0} value[2] of $0^{m}{\cdot}79$, the remaining discrepancy being only $0^{m}{\cdot}12$ and altogether without significance.

The one fly in the ointment is the mass ratio, which according to the orbital elements is only $1{\cdot}02 \pm 0{\cdot}03$ when, for the pair of stars proposed here as a model of HD 42994, it 'ought' to be about 1·12. The writer is not inclined to take that discrepancy too seriously, however, just as in the case of HD 25768, it would almost certainly be easy to 'correct' the apparent q value by making small adjustments to the adopted dip widths or ratio, but it seems unscientific actually to make such changes on purpose to bring q to heel. Obviously K_1 and K_2 would undergo slight revision, but no such change would be likely to affect P or T, and the effect on the other orbital parameters (γ, e, and ω) could be expected to be very small, although the standard errors ascribed to the adopted orbit must obviously be regarded as somewhat optimistic.

The $m_{1,2} \sin^3 i$ values given by the orbit are ludicrously smaller than the masses to be expected for stars of the types in the model, by a factor of the order of 60. It follows that $\sin i$ must be only about $1/\sqrt[3]{60}$ — just over ¼ — making the inclination 15° with little uncertainty. Utilizing that quantity, we find that the de-projected value of the separation of the component stars is about 2·5 AU. Since the orbit is seen almost face-on, that quantity represents nearly enough the actual semi-major axis of the orbit seen on the sky; it therefore ought to subtend about 2·5 times the parallax, or $0''{\cdot}04$, so it should be resolvable with telescope apertures above about 3 metres.

HD 215977

HD 215977 is a 7^{m} star about 4° preceding β Aqr; it is only about that same distance north of the celestial equator, so the observing season for it from Cambridge is rather short. In the absence of any ground-based photometry we must be grateful to *Tycho* for the values $V = 7^{m}{\cdot}27$, $(B - V) = 0^{m}{\cdot}48$. The only spectral classification appears to be the F5 in the *Henry Draper Catalogue*; it agrees reasonably well with the colour index. The *Hipparcos* parallax corresponds to a distance modulus of $4^{m}{\cdot}43 \pm 0^{m}{\cdot}16$, and thus to an absolute magnitude slightly brighter than +3. The revision[54] by van Leeuwen gives the modulus as $4^{m}{\cdot}18 \pm 0^{m}{\cdot}10$ and a magnitude therefore slightly *fainter* than +3.

At about the time that the Suchkov paper was written, but too late to be included in the paper, the slow apparent widening of the radial-velocity 'dip' abruptly reversed, and so did the nature of its asymmetry, after what was evidently quite a sudden periastron passage. The object was of course kept on the Cambridge observing programme, and another such passage has been witnessed recently. There are altogether 51 radial-velocity observations, all of which show a blended dip consisting of a wide and a narrow component; the former has about twice the equivalent width of the narrow one, but the latter is deeper. The profiles are always mutually blended, but are so different from one another that the radial-velocity traces can be reduced with all parameters 'free' at all phases of the orbit, even when there is very little velocity difference between the components. Fig. 7 illustrates a trace obtained near a node of the orbit. The rotational velocities of the two stars are quantified at 28 and 3 km s^{-1}.

The radial velocities measured from the 51 traces are set out in Table IV. Measurements of the wide and shallow primary dip are inevitably much less accurate than those of the sharp secondary, and have needed to be attributed a weight of only ⅟₁₂ to bring the variances for the two components into approximate equality. Five of the early traces were integrated for what in retrospect is regarded as too short a time, and/or were not scanned over a wide enough range

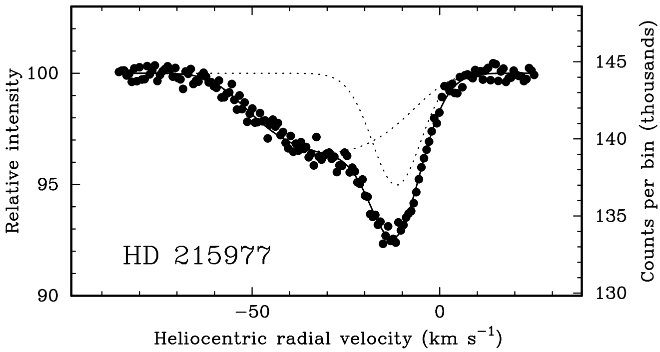

FIG. 7

Radial-velocity trace of HD 215977, obtained with the Cambridge *Coravel* on 2010 September 17, close to a node of the orbit.

of velocity to show satisfactory sections of 'continuum' at each end. They have been marked with colons in Table IV and down-weighted in the solution by a factor of four for the primary and two for the secondary. In the solution of the orbit the two components were found to give appreciably different γ-velocities, the discrepancy being 0·71 ± 0·21 km s^{-1}, with the primary more positive. Such a difference is unusual in the writer's experience, even though the need for a negative correction, increasing towards earlier types (but not yet definitely quantified and corrected systematically), has often been pointed out in papers in this series. The difference might be exacerbated by even a slight asymmetry in the profile of the primary dip. Whatever its actual cause, it has been artificially removed by making globally an empirical adjustment of –0·8 km s^{-1} to the velocities given for the primary in Table IV. The orbit is portrayed in Fig. 8, and its elements are:

P	= 3190 ± 10 days	$(T)_1$	= MJD 52485 ± 4
γ	= –20·09 ± 0·07 km s^{-1}	$a_1 \sin i$	= 263 ± 10 Gm
K_1	= 7·64 ± 0·29 km s^{-1}	$a_2 \sin i$	= 350 ± 4 Gm
K_2	= 10·15 ± 0·09 km s^{-1}	$f(m_1)$	= 0·072 ± 0·008 $M_\odot$
q	= 1·33 ± 0·05 (= m_1/m_2)	$f(m_2)$	= 0·168 ± 0·006 $M_\odot$
e	= 0·618 ± 0·006	$m_1 \sin^3 i$	= 0·517 ± 0·022 $M_\odot$
ω	= 274 ± 1·1 degrees	$m_2 \sin^3 i$	= 0·39 ± 0·03 $M_\odot$

R.m.s. residual (unit weight) = 0·40 km s^{-1}

Just as in the case of HD 42994, the 2:1 ratio of dip areas corresponds to $0^{m}{\cdot}75$ in terms of stellar magnitude, the implied *V*-magnitude difference of the components is about $0^{m}{\cdot}85$, and the total effect on the ΔMc_0 value should be to reduce it by about $0^{m}{\cdot}67$, actually to slightly below zero. The colour index of HD 215977 is also almost identical with that of HD 42994, so the same spectral types of F6 V and G1 V would suit both. The integrated absolute magnitude of $3^{m}{\cdot}21$, noted for the same combination of types for HD 42994, is about one standard deviation away from the value derived from the van Leeuwen[54] revision of the *Hipparcos* parallax.

TABLE IV

Cambridge radial-velocity observations of HD 215977

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
2000	Sept.	4·06	51791·06	−25·6	−15·7	0·782	−0·1	−1·2
		17·06	804·06	−20·8:	−13·8:	·786	+4·7	+0·6
		25·06	812·06	−22·2:	−14·0:	·789	+3·4	+0·3
		30·98	817·98	−20·9:	−14·6:	·791	+4·7	−0·4
	Oct.	8·94	825·94	−25·3	−14·6	·793	+0·4	−0·4
	Nov.	1·91	849·91	−21·0:	−14·0:	·801	+4·8	0·0
	Dec.	15·83	893·83	−27·1:	−13·2:	·815	−1·0	+0·4
2001	Jan.	6·74	51915·74	−24·4	−13·6	0·821	+1·8	−0·1
	July	24·05	52114·05	−25·8	−11·9	·883	+1·6	−0·1
	Oct.	3·93	185·93	−29·0	−10·7	·906	−1·2	+0·7
	Dec.	31·74	274·74	−26·2	−11·6	·934	+1·7	−0·3
2002	June	24·09	52449·09	−22·5	−18·9	0·988	0·0	−0·5
	Aug.	21·07	507·07	−18·9	−24·2	1·006	−0·9	+0·2
		29·04	515·04	−17·9	−25·2	·009	−0·5	0·0
	Sept.	9·06	526·06	−15·6	−25·8	·012	+1·1	+0·4
		29·93	546·93	−15·3	−27·7	·019	+0·1	+0·1
	Oct.	6·94	553·94	−12·3	−28·7	·021	+2·8	−0·4
		18·96	565·96	−14·7	−29·4	·025	−0·2	−0·4
		27·93	574·93	−13·2	−29·6	·027	+1·0	−0·1
	Nov.	3·94	581·94	−13·8	−29·7	·030	+0·1	+0·1
		21·89	599·89	−14·2	−30·7	·035	−0·8	−0·2
	Dec.	4·80	612·80	−10·9	−30·7	·039	+2·3	+0·1
		17·75	625·75	−13·1	−30·6	·043	−0·1	+0·5
2003	Jan.	5·74	52644·74	−14·8	−31·4	1·049	−2·0	0·0
		16·74	655·74	−11·2	−31·2	·053	+1·5	+0·2
	July	15·08	835·08	−14·0	−31·4	·109	−0·4	−1·1
	Aug.	16·08	867·08	−11·1	−29·6	·119	+2·7	+0·3
	Sept.	15·00	897·00	−12·4	−29·7	·128	+1·7	−0·1
	Oct.	27·87	939·87	−13·2	−29·7	·142	+1·3	−0·6
2004	Jan.	12·75	53016·75	−12·6	−28·2	1·166	+2·5	+0·1
	Aug.	20·07	237·07	−18·4	−26·2	·234	−1·7	0·0
	Sept.	15·02	263·02	−15·4	−26·2	·243	+1·4	−0·2
	Oct.	25·94	303·94	−14·8	−25·1	·255	+2·3	+0·5
2005	Aug.	13·10	53595·10	−19·4	−23·4	1·346	−0·7	+0·1
	Sept.	21·01	634·01	−18·1	−23·3	·359	+0·8	−0·1
2006	July	15·10	53931·10	−20·1	−21·2	1·451	+0·2	+0·1
	Sept.	20·03	998·03	−19·2	−21·2	·472	+1·4	−0·3
2007	Aug.	7·10	54319·10	−23·2	−18·9	1·573	−1·1	+0·1
	Sept.	16·04	359·04	−22·6	−18·8	·585	−0·3	−0·1
2008	July	30·11	54677·11	−24·1	−16·4	1·685	−0·3	+0·3
	Sept.	14·00	723·00	−21·8	−16·7	·699	+2·2	−0·3
	Dec.	17·79	817·79	−21·9	−16·0	·729	+2·6	−0·3
2009	Jan.	6·75	54837·75	−23·3	−16·2	1·735	+1·3	−0·6
	Dec.	6·82	55171·82	−26·5	−12·5	·839	+0·1	+0·5

TABLE IV (*concluded*)

Date (UT)	*MJD*	*Velocity* Prim. km s⁻¹	Sec. km s⁻¹	*Phase*	*(O–C)* Prim. km s⁻¹	Sec. km s⁻¹
2010 June 28·07	55375·07	−26·2	−12·4	1·903	+1·5	−1·0
July 22·12	399·12	−30·4	−10·9	·910	−2·6	+0·4
Aug. 28·08	436·08	−28·6	−11·2	·922	−0·7	0·0
Sept. 17·02	456·02	−28·9	−10·8	·928	−1·0	+0·4
Oct. 27·90	496·90	−25·7	−11·4	·941	+2·0	0·0
Nov. 15·90	515·90	−25·8	−11·2	·947	+1·7	+0·5
2011 Jan. 9·74	55570·74	−23·9	−13·3	1·964	+2·5	−0·2

The logarithm of the mass ratio, q, from the orbital elements of HD 215977 is 0·124 ± 0·016, which 'ought' to correspond to a difference approaching a whole spectral class between the components. The discrepancy between the two methods of estimating the spectral-type difference is larger than one would wish, but in view of the difficulties presented by the nature of the radial-velocity trace — always wide and blended — should probably not be regarded as serious. Without particularly wishing to denigrate his own work, the writer sees the raggedness of Fig. 8 (even after an empirical offset was made to the velocities of one component) as an invitation to regard the formal standard error of the value of q as an unrealistically low estimate of the true uncertainty: in making a compromise between the dip-ratio and mass-ratio estimates of the type difference, he would be inclined to give more weight to the former. In any case it has been noted above, with regard to HD 25768, how an explicit investigation demonstrated that q can be quite sensitive to the adopted ratio of dip strengths.

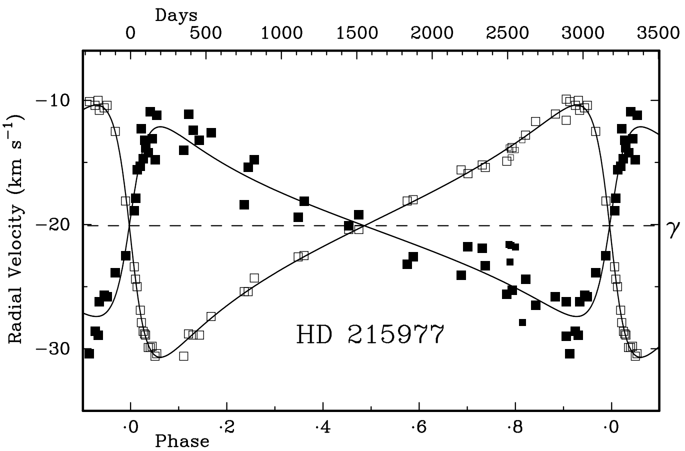

FIG. 8

As Fig. 4, but for HD 215977. The five *small* symbols for each component, near phase .8, represent certain early observations that are regarded as sub-standard and were down-weighted in the solution of the orbit (see text).

The mean rotational velocities of the components are, as noted above, 28 and 3 km s^{-1} for the primary and secondary, respectively. The former value is probably accurate to about 1 km s^{-1}, but the latter is less good, and might be better specified as $\lesssim 5$ km s^{-1}. The minimum masses, $m_{1,2} \sin^3 i$, demanded by the orbit are only about 40% of those to be expected for stars of the supposed types, so we can conclude that $\sin i \sim \sqrt[3]{0{\cdot}4}$, $\sim 0{\cdot}74$, whence $i \sim 48°$. The major axis of the relative orbit of the two components can be deduced from quantities in the informal table of orbital elements above, together with the value of $\sin i$, as $(a_1 \sin i + a_2 \sin i)/\sin i$, which amounts to about 5·5 AU. With $\omega \sim 270°$, the major axis of the orbit runs practically 'towards and away from us', though it is tipped at the inclination angle, so it is seen projected as $5{\cdot}5 \cos 48°$ AU, $\sim 3{\cdot}7$ AU; the maximum projected separation is greater by the factor $(1 + e)$, so is about 6 AU. That is clearly greater than the minor axis of the orbit, which is presented almost exactly 'in the plane of the sky'. Thus the maximum apparent separation should be observed near the actual apastron passage, and at the distance of nearly 70 pc the 6 AU should subtend an angle of some 0″·08. The system should therefore be easily resolved near apastron by speckle interferometry with telescopes of quite moderate aperture (2 m), but despite repeated suggestions by the writer to seemingly appropriate quarters over a number of years no report of resolution has so far been received.

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CAN THE DATE OF MOSES' DEATH BE DETERMINED ASTRONOMICALLY?

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There is an early Jewish tradition that the Sun darkened on the day of Moses' death. The possibility of this being a reference to a solar eclipse has been investigated. If such were to be the case, identification of the eclipse could be used to derive dates for events recorded in the Bible. A likely candidate eclipse has been found that fits well with Hebrew calendar dates and timelines that are recorded in the biblical books of Deuteronomy and Joshua.

Introduction

This paper explores the possibility that an early Jewish tradition can be associated with an astronomical event, and that this event can be used to derive dates for putative events recorded in the biblical books of Deuteronomy and Joshua. While not mentioned in those accounts, Jewish Midrash Rabbinic literature includes references to a tradition that the Sun darkened at noon on the day Moses died and that this darkness persisted until the ninth hour[1]. We have searched for a total solar eclipse that could explain this tradition and have found an intriguing candidate.

*Deceased

We recognize that previous efforts to use biblical narrative to date ancient events have met with mixed success. One can mention the plausible dating of the crucifixion of Jesus to AD 33 April 3[2]. A better-known example is the extensive body of work regarding the account in St. Matthew's Gospel[3] of the Star of Bethlehem associated with the birth of Jesus. A number of explanations have been offered to explain in modern terms what Matthew described, some of which would fix Jesus' birth date. One can mention, as examples, the works of Clark, Parkinson & Stephenson[4], Hughes[5], Humphreys[6], Molnar[7,8], Kidger[9], Larson[10], Teres[11], and Tipler[12] as a few of the many studies. Although many scholars feel Matthew's narrative is based on some actual astronomical phenomenon, no consensus has yet been reached as to exactly what the account refers. This suggests that the present results, which involve an even more ancient and more speculative astronomical event, should be treated cautiously. Nevertheless, we feel our findings are of sufficient interest to be placed on record.

Methodology

Our approach was, of necessity, based on the acceptance of the scriptural accounts. This does not mean that we adopted a strictly literal interpretation. For example, we would not construe a passage mentioning 40 years as necessarily meaning exactly that time period, but that it could be an approximation. However, when dates are explicitly given, as for example in Joshua 4:19 where it is stated "On the tenth day of the first month … ", we adopt them for our investigation.

A chronology was first established and then we sought a total solar eclipse that would have been visible in the Middle East around the (very uncertain) year of Moses' death. Modern astronomical software makes it easy to calculate the sky for any specified date and determine dates and visibility locations for eclipses. The difficulty arises in converting from the modern calendar system to the Hebrew calendar used in the scriptures. We have used the calendar converter maintained by John Walker that is available on-line[13]. This program allows one to enter a given date in the Gregorian Calendar, the Julian Calendar, the Hebrew Calendar, Julian Date system, or one of several other calendars and date-keeping schemes and retrieve the calendar date in the other systems. We tested the program using a few historical dates and other on-line Hebrew-to-Julian calendar-conversion tools and found it to be reliable. We caution, however, that the dates in which we are interested are well before any reliable test dates. Further, while it is known that the names of the months have changed since the earliest Hebrew calendar[14], we were forced to assume that there have been no major modifications in the structure of the calendar: a well-defined lunar-based calendar of twelve months per year with occasional additional months added to a year to maintain agreement with the solar cycle seasons. Without this assumption it is impossible to compare astronomically computed dates with the ancient records. For clarity we will utilize the presently used names for Hebrew calendar months and the Anno Mundi (AM) epoch for counting years.

Chronology 1 — the data

We started the development of our chronology by compiling the biblical information related to the death of Moses. A reading of the final chapters of Deuteronomy and the first ones of Joshua provides the following details: (*i*) Moses was 120 years old when he died on Mt. Nebo (Deuteronomy 32:50; 34:1–7). Mt. Nebo is about 18 km east of where the River Jordan enters the

Dead Sea. (*ii*) The Israelites grieved Moses' death for 30 days before they began preparing to cross the Jordan into the 'promised land' (Deuteronomy 34:8). (*iii*) The Israelites' first objective after crossing the Jordan was the capture of Jericho. In preparation, two spies were sent from the Israelite camp at Shittim into that city which was around 10 km distant. The spies spent at least part of one night hidden there and three days hidden in the surrounding hills before returning to their camp (Joshua 2:1–23). (*iv*) The Israelites moved their camp from Shittim to the banks of the Jordan, and after three days there they received instructions on how the Jordan was to be crossed (Joshua 3:1–3). (*v*) The Israelites finished crossing the Jordan on the 10th day of the first month, *i.e.*, on Nisan 10 (Joshua 4:19). (*vi*) Passover was celebrated on the 14th day of the month across the river at Gilgal (Joshua 5:10). (*vii*) The Israelites had been in the desert 40 years since the exodus from Egypt and the military-aged males were uncircumcised, so prior to the attack on Jericho they were circumcised at Gilgal and remained in camp until they were healed (Joshua 5:2–8). The attack took place some time after Passover.

The biblical chronology above has two specific dates (items *v* and *vi*). There are also some uncertainties in the timeline, especially item *vii* (healing time could be anywhere from a few days to a month or more) and in item *iii* (exactly how many days the spies are away from the camp at Shittim). The biggest difficulty, however, is the lack of the year for the dates mentioned. We therefore added to the above several other relevant pieces of information: (*a*) Passover is celebrated in the month of Nisan, the first month of the Hebrew calendar. Nisan always begins sometime in the spring. (*b*) A Midrash tradition holds that the Sun darkened at noon on the day Moses died and that this darkness persisted until the ninth hour (*i.e.*, 3 p.m.)[1]. (*c*) The most accepted period for Moses' life is in the 15th Century BC, although some scholars place it hundreds of years earlier or later[15]. (*d*) It is stated in 1 Kings 6:1 that Solomon began to build the temple in the 4th year of his reign, 480 years after the exodus. Solomon's reign generally has been dated to ~970 – 930 BC[15]. (*e*) Modern archaeology and radiocarbon dating give a date for the destruction of Jericho around about 1550 BC[16], although some have argued that its conquest was around 1400 BC[17].

Chronology 2 – derived dates

From the approximate dates of Moses' life and of Solomon's reign we adopted Moses' death as occurring about 1400 BC, with a large margin of uncertainty. We searched for pre-Passover (spring) eclipses easily visible in the vicinity of Mt. Nebo in the period 1630 to 1200 BC. The on-line version of the *Five Millennium Canon of Solar Eclipses*[18] was used, which gives the locations and dates of eclipses, in the Julian calendar and using an astronomical year for BC eclipses (*i.e.*, an additional year must be added to the dates given in the *Canon* to obtain traditional BC dates).

We looked for eclipses that met two criteria besides the date range 1630–1200 BC. First, the eclipse must have occurred in the period February to April. This derives from the fact that it would have happened at least 30 days prior to Passover, taking into account that this feast is moveable. Second, the eclipse must have been significant enough to attract attention. For this we adopted an eclipse magnitude of at least 0·7 at Mt. Nebo, taking into account that the uncertainty in ΔT produces possible shifts in the *Canon*'s eclipse maps of up to nine degrees of longitude.

Our results are shown in Table I. The table gives the traditional — not astronomical — year and Julian calendar day, the terrestrial time (TT) and computed local time of maximum eclipse, the type of eclipse and the nominal area of maximum visibility using modern place names. Those eclipses with maximum visibility away from Jordan would have been partial eclipses as seen from Mt. Nebo.

TABLE I

Spring solar eclipses visible in the Middle East 1630–1200 BC

BC Date	*TT (eclipse max.)*	*Local time*	*Eclipse type*	*Area of best visibility*
1605 Mar. 27	18:34	10:29	Total	Southern Saudi Arabia
1547 Feb. 15	19:42	11:56	Annular	Central Saudi Arabia
1523 Apr. 20	17:46	10:10	Total	Jordan
1429 Mar. 31	16:22	09:20	Total	Central Saudi Arabia
1399 Mar. 1	20:17	13:24	Hybrid	Jordan
1389 Feb. 9	21:52	15:02	Annular	Jordan
1345 Apr. 2	18:14	11:39	Hybrid	Southern Saudi Arabia
1335 Mar. 13	19:03	12:31	Annular	Syria
1281 Apr. 14	14:53	08:40	Annular	Turkey
1223 Mar. 5	18:49	12:54	Total	Turkey

The best candidate for an eclipse that meets our criteria is that of 1399 BC March 1. Not only did the path of maximum eclipse pass near Mt. Nebo, maximum eclipse occurred at the expected time of day. It is interesting that this eclipse was of the relatively rare hybrid type — those where the eclipse is total on part of the central path and annular on other parts. Such eclipses account for less than five percent of all solar eclipses.

Discussion

If one accepts the 1399 BC eclipse as the origin of the ancient tradition that the sky darkened on the day Moses died, then one has (keeping in mind that a new day begins at sunset in the Hebrew calendar and that the present conventions in that calendar system must be assumed) that Moses' death was on 1399 BC March 1 Julian = JD 1210498 = 2362 AM Adar I 29 (or perhaps Adar I 30 if the death occurred after sunset). We note that Jewish rabbinical tradition has that Moses died on Adar 7 while the Roman-era Jewish historian Josepheus gives Adar 1[19]. Assuming those dates refer to Adar II our result is not unreasonable. One also has: (*i*) The following day at sunset was the start of a new month — Adar II, since 2362 AM was an intercalary year of 29 days. (*ii*) Passover, at full moon, was JD 1210541·5 = Nisan 14 = evening of April 13 –April 14, which is 43 days after Moses' death. (*iii*) The crossing of the Jordan on the "tenth day of the first month" then was on 2362 Nisan 10 = JD 1210538, or 40 days after Moses' death. One should note that Nisan is the first month of the biblical (or Jewish-festival) year, but because the Hebrew-calendar civil year begins six months later with Tishri the year number was still 2362 AM.

Forty days between Moses' death and the crossing of the Jordan is not inconsistent with a careful reading of the biblical account. If we sum the days of the various events between Moses' death and the crossing of the Jordan, we have:

30 = thirty days of mourning (Adar I 30 and Adar II 1–29, *i.e.*, until the start of a new year)

4 = four days spies were away to Jericho (one day in that city, three days hiding in the surrounding hills)

1 = one day for the spies to return to the Israelite's camp at Shittim
1 = one day to move the camp from Shittim to the banks of the Jordan
3 = three days of preparations for the crossing of the river
39 = total number of days of activities before the crossing was made, which occurred on the following day, or 40 days after Moses' death.

Thus, based on the assumption that the sky was darkened at Moses' death and that this was from a solar eclipse, not only is the date of Moses' death established but also an internally consistent chronology can be derived which matches the specific Hebrew calendar dates given in the Bible.

Accepting 1399 BC for the year of Moses' death and that the biblical records are (at least approximately) accurate, one can derive dates for other biblical events associated with Moses' life. First, it is stated in Deuteronomy 34:7 that Moses was 120 years old when he died; if 120 years is not a figurative statement our results put his birth year around 1519 BC. This places Moses' birth during the reign of the pharaoh Amenhotep I (Djeserkara) using one commonly accepted chronology for the Egyptian rulers[20]. Amenhotep's reign began in ~1525 BC, which would be in accord with the report in Exodus that Moses was born a little after a new pharaoh came to power. Second, the Bible records that at the time of Moses' death the Hebrews had been in the desert for 40 years, which would make it about 1440 BC when Moses led the Jews out of Egypt. That would make Thutmose III (Menkheperre) the pharaoh of the exodus, again using our adopted chronology of the pharaohs and assuming 40 years is not figurative. It must be noted, however, that not only is the chronology of Egyptian rulers for this period not firmly established and there are several other pharaohic possibilities, but some scholars question the reality of the biblical account. An introduction to the different viewpoints can be found in Howard & Grisanti[21] (see, in particular, the essay by Shea on the date of the exodus).

Finally, one can also seek unusual astronomical phenomena — 'signs' — at the time of other key points in the life of Moses, namely his birth and the exodus. While we have done such a search, the results will not be reported here as they are inconclusive.

Final remarks

It has been shown that the hypothesis that a solar eclipse occurred on the day Moses died leads to a date of his death being 1399 BC March 1 (Julian calendar). It also leads to a chronology consistent with the biblical narrative of Moses' death, which includes several specific dates in the Hebrew calendar. Nevertheless, several difficulties exist with this result. First, we note that our derived date is in disagreement with the traditional Jewish chronology *Seder Olam Rabbah*, which gives a Hebrew date of 2488 AM, or 1273 BC[22]. This date is about 130 years later than our results. This might be explained by noting that the 2nd-Century-AD author of the *Seder Olam* seems to have adopted three principles in deriving his chronology: (*i*) to assume that the intention of the biblical author was, wherever possible, to give exact dates, (*ii*) to assign to each of a series of events the shortest possible duration of time, where necessary, in order to secure agreement with the biblical text, and (*iii*) to adopt the lesser of two possible numbers. The latter two principles will, if applied erroneously, lead to early events (such as death of Moses) being dated later than when they occurred. In contrast to the *Seder Olam* date, radiocarbon dating and archaeological evidence for the destruction of Jericho, which in the biblical narrative occurs shortly after Moses' death, points to a date of about 1550 BC[16], or about 150 years earlier than our result. There is again a possible explanation, in this case that the extrapolated stratigraphic calibration used for this result yields dates 100 years earlier than those from another radiocarbon analysis of similar samples[16,23]. In summary, the inconsistencies in the results from various approaches underline the extreme difficulty in both dating and establishing the validity of the biblical record. Greater minds than ours have wrestled with this matter with little success (for example, see Newton[24]).

Postscript

This study was the idea of the senior author, Thomas Manetsch. Dr. Manetsch unfortunately passed away on 2011 January 1 as a draft of this paper was being prepared. This article is dedicated to his memory.

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CORRESPONDENCE

To the Editors of 'The Observatory'

The Ancient Colour of Saturn

Two colours were traditionally assigned to the planet Saturn in Western antiquity: black and yellow. In the case of the four other planets known at the time (Mercury, Venus, Mars, and Jupiter) the colours usually assigned were essentially those perceived today by the naked eye, although atmospheric and other conditions sometimes led to other colours being assigned[1]. Saturn today is yellowish. Why, then, was it explicitly called 'black' in the Babylonian cuneiform texts and in Graeco-Roman writings that were dependent on the Babylonian tradition?

James & van der Sluijs[2] have wondered whether the enormous Phoebe Ring which surrounds Saturn with a diameter of about two full moons as seen from the Earth might have been much brighter, since it is visible today only in the infrared. If so, Saturn's appearance would have been that of a large black oval enclosed within a bright ring and punctuated with an interior yellow dot. According to James & van der Sluijs, ancient testimony supports the idea of such a huge 'black' Saturn.

Here I will show that the same testimony can support an alternative interpretation of Saturn's two perceived colours that is based on a more conventional picture: 'yellow' when the planet was high in the sky and 'black' at the times of its heliacal risings and settings.

At least two ancient Greek authors described Saturn as yellowish. Plato (*Republic* 10·14) associated Saturn's colour with that of the Sun and Moon, calling it 'yellower than the Moon.' In the 5th Century AD, Hephaestion of Thebes (*Apotelesmatica* 1·24), discussing the properties of the 'disceus' comet, described it as 'round and electrum-coloured like Saturn', electrum being a compound of gold and silver. The Babylonians themselves linked Saturn to the Sun ('son of Shamash', 'star of Helios'), presumably because of its similar colour, yellow, and termed the planet a 'night sun'.

In their standard lists of planetary colours, however, the Babylonians always gave Saturn's colour as 'black'. Why? I suggest that, because the planet was associated with the Sun, its heliacal risings and settings were more important than for the other planets, even though for all of the planets the heliacal risings and settings possessed special astrological significance. A rather faint object like Saturn (two magnitudes fainter than the brightest star Sirius) appears dim gray when seen through the thick layers of the atmosphere near the horizon. This is because the human eye cannot distinguish colours at low light levels. Thus the choice of 'yellow' or 'black' by the Babylonians would have come down strongly in favour of 'black' as the dominant colour of Saturn.

Indirect support for this interpretation comes from the Babylonians' invariable description of the colour of Sirius as 'red'[3], even though it is today a white star at high sky elevations. The Babylonians associated Sirius with the Sun and always recorded it for calendrical and other purposes at its heliacal risings, when it would usually appear reddish[4]. On the other hand, various Graeco-Roman writers described Sirius as either 'red' or 'white', indicating that in antiquity its apparent whiteness was well known. The analogy with Saturn is clear.

So which of the two interpretations of Saturn's 'blackness' is correct — the Phoebe Ring hypothesis or the heliacal-rising-and-setting hypothesis? The answer will probably require further study based on the acquisition of more evidence and analysis.

Thanks are extended to Marinus van der Sluijs for informing me about his work with Peter James on Saturn and for much correspondence concerning the two hypotheses. David Hughes, as the referee, also made some useful suggestions.

Yours faithfully,
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REVIEWS

Lunar Meteoroid Impacts and How to Observe Them, by B. Cudnik (Springer, Heidelberg), 2010. Pp. 271, 23·5 × 18 cm. Price £24·99/$34·95/€34·95 (paperback; ISBN 978 1 4419 0323 5).

The existence or otherwise of transient lunar phenomena, or TLPs, has long been an issue that divides observers of the Moon and one that has given rise to much, often acrimonious, debate. However, all are agreed that one category of TLP is undoubtedly real: the momentary and elusive flashes created by meteoroids striking the un-illuminated portion of Moon's disc. It should come as no surprise, given the extensive rôle played by bombardment in shaping the lunar surface, that the process is still on-going today, albeit on a much lesser scale than in the past. Yet it is only in the last few decades that systematic attempts have been made to detect impact flashes telescopically, and we had to wait until 1999 for the first confirmed observation — fittingly, by the author of this very useful volume. Subsequently a great many more impact flashes have been observed and confirmed, both by amateurs and by professionals working at NASA's Marshall Space Flight Center.

This volume follows the pattern established by previous books in this series, with Part 1 providing an historical overview of impact cratering, not only on the Moon but throughout the Solar System, along with a treatment of crater morphology. This is useful background, but it has been done elsewhere and the more experienced reader may be inclined to skip it. Chapters 3 and 4, on specific suspected lunar events, tread less-familiar territory, but the real value of this book is to be found in the chapters that comprise Part 2. These serve as a practical guide to observing lunar meteoroid impacts and they introduce the serious amateur to a programme of observational work that can truly yield valuable results and allow genuine professional–amateur collaboration. Cudnik gives sound advice on observational techniques and preparation, on the choice of equipment for the detection and recording of lunar impacts, and on how to construct an appropriate routine for observing and reporting in collaboration with amateur and professional colleagues. He also discusses ways in which the search for impact flashes might be automated through the use of video cameras and detection software, as well as how to avoid being confused by other 'flash' phenomena such as camera noise, cosmic rays, Sun glints off Earth satellites, *etc*. Small, specialized sections of these discussions are entrusted to secondary authors.

There are some weaknesses in this volume, but generally they are related to production, and a more rigorous proof-reading would have picked up slips and instances of repetition. But it is the reproduction of illustrations that most lets down this volume. Often their quality is simply not good enough to reinforce the text, and sometimes images are mislabelled. Bizarrely, the jacket illustration for a book on lunar meteoroid impacts shows a radar image of a crater on Venus!

Despite these shortcomings, this is a valuable book on an important observational opportunity for the amateur, and Cudnik is to be congratulated on writing a clear and compelling tutorial on how to go about such work. — BILL LEATHERBARROW.

Planets: A Very Short Introduction, by D. A. Rothery (Oxford University Press), 2010. Pp. 135, 17 × 11 cm. Price £7·99 (paperback; ISBN 978 0 19 957350 9).

That the first-known written suggestion that the Earth goes round the Sun occurs in a 9th-Century BC Indian text, that the hole in the ozone layer has little to do with global warming, and that Ceres is the only dwarf planet which is not a Plutoid, are but three of the many nuggets of information which I enjoyed finding in this book.

Its title, *A Very Short Introduction*, is a misnomer for a book of 135 pages but is forced upon it as one of a series of *Very Short Introductions* now being published by the Oxford University Press, and 'A Concise Introduction' would do it more justice. The book is also disconcertingly small, and being in soft-back format looks at first glance more like a railway timetable (of the modern kind — not the mighty Bradshaw of yore) than what I would call a proper book. But these are quibbles, because inside it is just about all the information that an interested layman would want to know about our local planets, with a brief word about exoplanets as a concluding bonus.

The author opens with a review of the Solar System as a whole, and goes on to describe in more detail the eight planets and their satellites, asteroids, comets, Centaurs, and trans-Neptunian objects. He writes with an enthusiasm for his subject, and particularly the satellites of the giant planets, which transmits itself to the reader, and his up-to-date account of past, present, and planned space probes, and the extent to which the information obtained from them has increased and altered our comprehension of what is out there, is clear and helpful.

Current theories regarding the formation and subsequent adventures of the various objects that make up the Solar System are well described, and current lacunae are not glossed over (*e.g.*, the capture by Mars of Phobos and Deimos is succinctly described as "not understood"). I was glad to read a simple account of the demotion of Pluto from planetary status, initially reclassified as a mere dwarf planet but then elevated to the rank of Plutoid, and while on the subject of names I was interested to note that exoplanets are not named but given numeric references. The author points out that exoplanets may already have been named by their inhabitants, but this argument has never inhibited us from naming stars, a point that famously puzzled the questioner at one of Sir James Jeans' lectures (how, she asked, did we know the names of the stars?). The book has a number of illustrations that, while inevitably restricted in their quality by the format, adequately support the points made in the text.

An advantage of a concise, rapidly assimilated book like this is the opportunity it gives the reader to reflect upon and even attempt to identify some of the key elements in the overall picture painted by the author. I am lost in wonder and admiration of the observational techniques that have now been developed not only to detect and analyze distant space objects but also, *via* radiometric dating, to deduce an accurate timing of distant past events. It is also clear that the human instinct to take comfort from the apparently ordered and majestic symmetry of Sun and planets is not much more than wishful thinking, bearing in mind the amount of dust and chaos out there. One is again given cause to tip one's hat to the primitive algae and their successor plants which have contrived over billions of years to give to Earth, uniquely, an atmosphere enabling us to exist. And in conclusion, to mark the fortunate fact that it does all hang together, I am tempted to rewrite Joseph Addison's famous ode so as to make the last verse read:

In Reason's ear they all rejoice,
And utter forth a glorious Voice
From Chromo and Nephelosphere
"Tis Gravity that holds us here".

Despite, then, my initial reservations about the book's apparent lack of *gravitas*, my conclusion is that it is a lucid, adequately comprehensive, and (on account, I am forced to admit, of its size) handy compendium of current planetary facts and theories. I enjoyed reading it, and shall be looking out for other books in this OUP *Very Short* series. — COLIN COOKE.

Moonwalk With Your Eyes: A Pocket Field Guide, by Tammy Plotner (Springer, New York), 2010. Pp. 360, 20·5 × 12·5 cm. Price £31·99/$34·95/€34·95 (paperback; ISBN 978 1 4419 0645 8).

Depending on the weather and the time of month, the Moon is there in the sky for you to gaze upon, but if you have never looked at it through a telescope a fascinating world to explore awaits you. Amateur astronomer Tammy Plotner takes you on a journey with your eyes to learn in a very non-technical entry-level manner what to see on the Moon. She also instructs you on how the Moon moves through our night and daytime skies.

The book is divided into a chapter for each day of a lunation cycle (from new moon to full and back to new moon). The author takes you for a daily "moonwalk" through a lunation, stopping along the way to learn about what you are observing. The last eight chapters are handy tables of the dates of the Moon's phases, a time-conversion chart, and a lunar log journal where you can log in the features that you have observed.

Since there is nothing to observe from Earth on the first day of a new lunation (new moon), the author uses this time to give you tips on purchasing binoculars and/or telescopes. The different types of telescopes and eyepieces are explained. Plotner tells you the advantages and disadvantages of each of the popular telescope and eyepiece designs. The book contains numerous annotated amateur and spacecraft images that clearly show you what the author wants you to observe when you are at the telescope.

I thoroughly enjoyed reading this guide to observing the Moon. I highly recommend it to anyone interested learning about our celestial companion. You will have hours of enjoyment as this book opens up the Moon to your eyes. — ROBERT GARFINKLE.

The Cambridge Star Atlas, by Wil Tirion (Cambridge University Press), 2011. Pp. 90, 30·5 × 24 cm. Price £23·99/$32·99 (spiralbound; ISBN 978 0 521 17363 6).

This is the fourth edition of a widely admired star atlas. The second was reviewed in *The Observatory*, **117**, 102, 1997. The author is well-known for the excellence of his cartography which has appeared not only in earlier editions of this atlas, but in many other books. The main part of this atlas consists of twenty charts in equatorial co-ordinates (2000·0) at a scale of 0°·3/mm, reaching to magnitude 6·5. There is one map per opening, designed to be read in landscape format. The left-hand page (above) has lists of the galaxies, nebulae, clusters, double stars, and variables which appear in the chart below. The right-hand page (below), contains the chart, 76° × 56°, with generous overlaps, usually more than 10° on all sides. However, the lists on the page above contain an object only on the first occasion it appears, and do not contain duplicates in the overlap regions. The main Milky Way is shown as white, the outer parts in pale blue, and the rest of the sky in darker blue. The listed objects are colour-coded on the charts and the larger nebulae are drawn faithfully in size and shape. These charts are simple rectangular or polar plots, but the inevitable small amount of distortion in the corners is negligible.

There are six maps of the whole sky in Galactic co-ordinates on Mollweide's equal-area projection. This projection is not isomorphic, so some constellations have scarcely recognizable shapes. They show the distribution of different types of clusters and nebulae with respect to the Milky Way.

The Moon is shown in two orthographic maps of 24-cm diameter, both with south at the top, one with east on the left and the other on the right. There is a key with 250 objects, given as conversion of number on the chart to name, and conversely in alphabetical order.

The hemispherical seasonal maps are on the stereographic projection; four for the northern sky at six-hour intervals and another four for the southern sky. In the north the maps for latitudes 20°, 30°, 40°, and 50° are superposed, and in the south 10°, 20°, 30°, and 40°, so that the majority of Earth's population can find a suitable horizon. Because of the geometry of the stereographic projection all four horizons are circles, but they are drawn as black on blue and are easy to muddle up. The projection makes the shape of the constellations correct over small areas but has a scale which increases from zenith to horizon. The stars α and β Orionis are separated by 17 mm on the northern winter map but 29 mm on the northern autumn. Stars brighter than the fifth magnitude are shown as white dots on a blue background and the constellations are shown as stick figures in yellow. The Milky Way is shown in a paler blue. Because the maps are separated by six hours it is difficult to find constellations during the hours in between. The third edition of this atlas was more convenient with maps at monthly intervals.

This atlas is doubtless intended for use outdoors. It is printed on durable paper — durable enough to resist spilt tea — and is spiral bound to make it convenient for use with telescope or binoculars. It should prove popular with a wide readership. — DEREK JONES.

Patrick Moore's Data Book of Astronomy, by P. Moore & R. Rees (Cambridge University Press), 2011. Pp. 576, 28 × 22·5 cm. Price £35/$55 (hardbound; ISBN 978 0 521 89935 2).

Patrick Moore's Data Book was previously published a decade ago by the Institute of Physics. This new, enlarged edition brings it up to date. It has a very clear and lively text, but I suspect its greatest value will be in terms of the many reference tables scattered throughout its considerable bulk. The illustrations are all in black and white, and sensibly portray maps of all sorts from planetary and satellite surfaces to each of the constellations.

In such a large work, typographical errors are inevitable, and I casually noticed that NASA's *Phoenix* was aerobraked by the Martian atmosphere from 21 000 km h^{-1} to 8 km s^{-1}, and that there is something odd about the dates of the old occultations of Uranus by the Moon. The text frequently uses 'I' and 'my' where the senior author is expressing his views.

This will be a tremendously useful text to dip into. Tables cover named planetary features, minor-planet orbits, meteorite falls, Earth's geological periods, spacecraft, objects of note in constellations, observatories, notable astronomers, *etc*., *etc*. Martin Rees, in his Foreword, writes of the 'immense labour' that must have gone into the *Data Book*, and that 'it is surely unique in gathering such a wide and eclectic range of information into a single volume'. Your reviewer agrees. — RICHARD MCKIM.

The Lives of Stars, by K. Crosswell (Boyds Mills Press, Honesdale, PA), 2009. Pp. 72, 31 × 23·5 cm. Price $19·95 (about £12) (hardbound; ISBN 978 1 59078 582 9).

Many coffee-table books are large and heavy as well as being beautiful, and seem designed to impress rather than impart information. This book is different. Although in fairly large format (a little bigger than A4), it is slim and aims to tell a coherent story about stars as well as providing lavish illustrations. It is certainly colourful — almost every two-page opening contains at least one picture, and there are no white pages (so the print is black on light-coloured pages and white on dark-coloured ones). However, the text is what makes this book more than just a coffee-table ornament. It starts from absolute basics, saying what stars are, and then works systematically and clearly through a succession of topics, including how stars shine, where and how they are born, the H–R diagram, main-sequence and giant stars, brown dwarfs, planetary nebulae and white dwarfs, supergiants and supernovae, end states (neutron stars and black holes), multiple stars and star clusters, the origin of the elements, extra-solar planets, and life in space. The style is simple and readable, and the relevant physics is described without too much over-simplification, including the balance between pressure and gravity, the key rôle of gravity, and even the physics of electron and neutron pressure ("Two electrons don't 'like' to be in exactly the same place, just as two people in a movie theater don't like to sit in the same seat").

Of course, it would be surprising if there were not some things to make a professional grimace, and a couple jumped out at me. On p. 7, the Kelvin scale is introduced by saying that "Kelvin is a temperature scale that astronomers use", which is somewhat misleadingly narrow, suggesting (although admittedly not actually saying) that only astronomers use it. I was pleased to see that the concept of stars having negative specific heat was introduced on p. 15 (not in those words, of course), but disappointed by the implication that only new-born stars behave that way ("Because of gravity, a newborn star is the only thing that loses heat yet gets hotter"). There may be other such minor misrepresentations, but I stopped being so critical at that point and just enjoyed reading.

The book has a nice glossary, and a useful index, but it is a pity that it contains no suggestions for further reading. However, it is suitable for complete beginners and might make a nice Christmas present for a teenage relative who is showing an interest in astronomy (I tried it on my 10-year old grand-daughter, who thought it would be suitable for children a little older than her), or indeed for one of your non-scientific adult friends or relations. — ROBERT CONNON SMITH.

3D Spectroscopy in Astronomy (Canary Islands Winter School of Astrophysics, Vol. XVII), edited by E. Mediavilla, S. Arribas, M. Roth, J. Cepa-Nogué, & F. Sánchez (Cambridge University Press), 2010. Pp. 271, 25 × 18 cm. Price £70/$115 (hardbound; ISBN 978 0 521 89541 5).

This new volume in the Canary Islands Winter School series continues the fine tradition of providing a thorough summary of an area of astronomy, at a level aimed squarely at graduate students. 3-D spectroscopy goes by several names, reflecting a variety of technical approaches, but all have the feature of providing simultaneous spectral information from multiple points on the sky — beyond the information provided in only two dimensions by conventional slit spectroscopy. The techniques explored and explained in this volume have seen most application in European astronomy, and this volume provides a European perspective, but 3-D spectroscopy is an area with rapidly expanding applications both in ground- and space-based astronomy, and as a result, publication of this volume is timely.

I have had the pleasure of working with several of the experts assembled for this school, and can vouch that the organizers did a fine job in their selection. The result is a thorough exposition on the subject, starting with the "what is 3-D spectroscopy" question and extending right down to tutorials on using the P3D software package, which is becoming a standard, at least in Europe. Roth's opening summary sets the stage for the following chapter by Turner where he goes right back to the basis of what makes good data, 3-D or otherwise. This should be required reading for anyone dealing with data. The third chapter, by Bershady, deals with spectrograph design, and is also a fine and comprehensive general introduction.

The only place where this volume doesn't hit the mark is that the chapters do not connect as well to each other as one might want. This is the result of the format of the Winter School, with separate lectures, each written up independently. The chapters on data analysis (Ferruit) and the P3D tutorial (Sanchez) are fine in themselves, but would have benefitted from being more closely related to each other and to the principles laid out in Turner's chapter, for example. That said, the P3D tutorial is exactly what is needed to help break down the perception that integral-field data are difficult to reduce.

I recall a conversation with an eminent instrumentalist a decade ago where he lamented the fact that so few papers have resulted from Fabry-Perot-etalon observations (one of first the 3-D techniques). He ascribed this state of affairs to the difficulty in dealing with the data, but also to the perception among many astronomers that it would "take a year" to analyze a night's data. It is to the credit of those involved in Euro3D and in developing the P3D software package that 3-D spectroscopy is now seen as increasingly mainstream and is viewed as much less daunting. As that happens, this volume will be seen as a milestone. It deserves a place in any graduate-level observational-techniques and instrumentation class. — GARY J. HILL.

The Dynamic Interstellar Medium: A Celebration of the Canadian Galactic Plane Survey (ASP Conference Series, Vol. 438), edited by R. Kothes, T. L. Landecker, & A. G. Willis (Astronomical Society of the Pacific, San Francisco), 2010. Pp. 444, 23·5 × 15·5 cm. Price $77 (about £50) (hardbound: ISBN 978 1 58381 756 8).

As the title says, this volume is the proceedings of a conference to celebrate the Canadian Galactic Plane Survey (CGPS). However, readers should not take that to mean that the volume focusses solely on that primarily radio survey of the northern Galactic plane. Although several of the papers are based on CGPS data, the majority are not. The volume covers a range of topics related to the interstellar medium (ISM), including observations made at a range of wavelengths, and not just in the radio. Moreover, the contributions cover the various aspects of the ISM in nearby galaxies as well as in our Galaxy, and also provide a section on future prospects in those areas. The volume contains more than a dozen review papers, typically of about 15 pages, which are useful overviews of a wide range of topics (*e.g.*, dust, molecular clouds, neutral hydrogen, and other components of the ISM, plus magnetic fields in our Galaxy and nearby galaxies, *etc.*). In addition there are about forty other, shorter papers that discuss particular issues in more detail. One criticism I have is that many of the figures seemed far too small to be appreciated properly. Overall this book is to be recommended, at least as a library purchase, as it provides a useful and up-to-date overview of a wide range of observational studies of the ISM in our Galaxy, plus some topics related to nearby galaxies. — DAVE GREEN.

The Multiwavelength Atlas of Galaxies, by G. Mackie (Cambridge University Press), 2011. Pp. 256, 28·5 × 22 cm. Price £90/$145 (hardbound; ISBN 978 0 521 62062 8).

This attractive book contains a wealth of well-reproduced, full-colour images of galaxies. It seeks to illustrate the diversity of structures that the Universe provides in these objects, and, even more strikingly, how much the appearance of a galaxy depends on your wavelength of choice.

Ultimately, though, it is not clear at whom the book is directed. Some of the text is of a relatively technical nature, with a variety of equations that may scare off the casual reader. This would be unfortunate, as the equations really are not necessary to appreciate the images, and, indeed, are never used after they have been introduced; but that rather begs the question as to why they are there at all. The more descriptive text is quite informative, but does not contain any particular new insights into our understanding of galaxies and their history; indeed, it perpetuates the urban myth (which in my time I have also propagated) that Hubble used the terms "early" and "late" to describe galaxies because he thought they represented an evolutionary sequence, whereas he actually put a footnote in his paper where the terms were introduced saying that they should absolutely *not* be interpreted in this way.

Clearly, the main components of the book are the images, but there again the reader is left wondering quite what to make of them. By the very nature of the range of wavelengths covered, many are shown in a variety of false-colour renderings, but nowhere is this central point of a multi-wavelength picture book explained. Since the images are taken from existing resources, there is also no uniformity in presentation, with similar wave-bands shown using entirely different colour schemes for different galaxies, making it difficult to compare and contrast those systems (which surely was the point of the atlas). Even for a single system, images in different wave-bands are presented at different scales, again making it difficult to contrast galaxies' appearances across wavelengths.

Ultimately, though, the biggest problem with this book is its price: at £90/$145, even libraries are likely to baulk at buying it without a clearly identifiable readership. In the past, one could have argued that it would make a nice coffee-table book for the wealthy, but nowadays they would surely be more likely to leave an iPad lying around with any of the wealth of free internet images of galaxies displayed on it. — Mike Merrifield.

Principles of Adaptive Optics, 3rd Edition, by R. K. Tyson (CRC Press, Boca Raton, FL), 2010. Pp. 299, 24 × 16 cm. Price £57·99 (hardbound; ISBN 9781 439 80858 0).

Previous editions of *Principles of Adaptive Optics* shared with John Hardy's 1998 *Adaptive Optics for Astronomical Telescopes* the distinction of being the standard teaching and reference monographs for the subject. The third edition of Robert Tyson's book, fully updated with the many advances over the last decade, must now become the standard academic text. It will also become the preferred read for anyone seeking an in-depth introduction to the capabilities of adaptive optics — and its many limitations.

The sometimes-spectacular correction of atmospheric seeing on large ground-based telescopes has brought adaptive optics to prominence, but an accurate understanding of its true capabilities requires a very serious introduction. With a vast and ever-expanding technical literature to navigate, an up-to-date, well-structured, and comprehensive single text is essential for the newcomer. *Principles of Adaptive Optics* meets this need well, exploring as it does the restrictions on the corrected field of view, the coverage of the sky, and the strong dependence of the technique's performance on environmental conditions. The book also describes how these limitations have driven recent developments in laser guide stars, and the current intensive research into advanced wide-field adaptive-optics systems.

The book is strongly recommended for those involved in building an adaptive-optics system, perhaps for an engineer in one discipline seeking an understanding of the wider design issues. The section on adaptive-optics system engineering is especially useful in this respect. This system-level view is provided alongside the detailed description of the various components, such as wave-front sensors, deformable mirrors, and control systems. It should be noted too that non-astronomical applications of these technologies are also well described. The book ends with an excellent and comprehensive bibliography. — RICHARD MYERS.

PAPERBACK RELEASE

Fred Hoyle: A Life in Science, by S. Mitton (Cambridge University Press), 2011. Pp. 369, 23·5 × 15·5 cm. Price £19·99/$36·99 (paperback; ISBN 978 0 521 18947 7). Reviewed **125**, 331, 2005.

OTHER BOOKS RECEIVED

Black Holes, edited by M. Livio & A. M. Koekemoer (Cambridge University Press), 2011. Pp. 321, 25 × 18 cm. Price £70/$115 (hardbound; ISBN 978 1 107 00553 2).

These proceedings collect twenty of the invited talks given at a Space Telescope Science Institute symposium held in 2007 April. They cover a wide range of topics and will be a valuable benchmark for researchers working in this general area of astrophysics.

Learning from Inquiry in Practice (ASP Conference Series, Vol. 436), edited by L. Hunter & A. J. Metevier (Astronomical Society of the Pacific, San Francisco), 2010. Pp. 586, 23·5 × 15·5 cm. Price $77 (about £50) (hardbound; ISBN 978 1 58381 752 0).

This volume contains the proceedings of a conference held in the Center for Adaptive Optics at Santa Cruz, California, in 2010 January. The focus of the meeting was the professional development of scientists for careers in teaching, and some aspects of astronomy were included as examples of the various approaches taken.

THESIS ABSTRACT

THE MICROWAVE BACKGROUND BEYOND THE POWER SPECTRUM

By Duncan Hanson

The minute fluctuations of the Cosmic Microwave Background (CMB) are a cornerstone of modern cosmology. They characterize the small perturbations in the distribution of matter and energy in the early Universe, and have been used with great success to hammer out the details of the current concordance model.

The connection of CMB observations to science is most often made by using their power spectra, which completely characterize the fluctuations if they are Gaussian and statistically isotropic. The amount of information contained in the temperature power spectrum will soon be exhausted, however, with the recently launched *Planck* satellite expected to measure almost all of its primary features with high signal-to-noise. There is fortunately still a large amount of useful information contained in the data if we allow that the fluctuations may be statistically anisotropic and non-Gaussian. Such models arise both from potential early-Universe physics as well as astrophysical secondary effects.

We study in detail the analysis of the CMB fluctuations beyond the power spectra, treating statistical anisotropy and non-Gaussianity in a unified framework which is based on quadratic building blocks. We first demonstrate this formalism in application to the data from the *WMAP* satellite, constraining modulations of the observed and primordial fluctuations with quadratic maximum-likelihood estimators. The power of this approach lies in its speed and ability to test for systematic effects, which we use to resolve a previously unexplained nine-sigma anomaly in the *WMAP* data as a result of contamination from the asymmetric instrumental beams. We then proceed to make a detailed study of the non-Gaussian effects due to gravitational lensing of the CMB by large-scale structure. In particular, we perform a detailed study of non-Gaussian estimators for the lensing potential power spectrum with simulated *Planck* data, discovering and correcting a number of small biasses due to the high signal to noise with which lensing will be measured. — *University of Cambridge; accepted 2010 August.*

Here and There

LIES, DAMN LIES, AND ASTROPHYSICS

Despite only having a sample of one from that distant past, — says that galaxies in the early Universe have fairly uniform properties, therefore it is possible to draw over-reaching conclusions. — *Astronomy Now*, 2011 March, p. 18.

DOUBLE VISION

[the Maldives] So close to the equator that you can see stars from both hemispheres — *Qantas* [in-flight magazine], 2011 February, p. 77.

PERHAPS IN THE HOGWARTS' LIBRARY

This time-lapse image from NASA shows the largest solar explosion in four years — *[London] Metro*, 2011 February 18, p. 11.

SO THAT CLEARS IT UP!

… we are hesitant to produce detailed figures regarding any "best-fit" jitter parameters arising from our analysis. However, for the sake of completeness, we note that the analyses … find overall system jitter levels of $\sigma_j = X^{+Y}_{-Z}$, $\sigma_j = X^{+Y}_{-Z}$, and $\sigma_j = X^{+Y}_{-Z}$, respectively. — *ApJ*, **729**, 98, 2011.