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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2021 October 8 at 16^{h} 00^{m}
held on-line

Michael G. Edmunds, *President-Elect*
in the Chair

The Chair. Welcome everybody to the October Open Meeting of the Royal Astronomical Society. This meeting is taking place, as you'll realize, *via* webinar. If you look to the top left of the screen, you should see a small green shield. This symbol means that you're using the most up to date version of Zoom, and that it is secure. Questions can be asked at the end of today's lecture, but you will be muted. Please use the chat facility, and only the chat facility, not the question and answers, found at the bottom of your screen. Your questions will go only to the panellists, and then they'll be read out by the editorial team member, Dr. Louise Alexander, for the lecturer to answer at the end of the talk.

It now gives me very great pleasure to introduce our George Darwin Lecturer for this year, Professor Filippo Fraternali, Professor of Gas Dynamics and the Evolution of Galaxies at the Kapteyn Astronomical Institute of the University of Groningen in the Netherlands. He obtained his PhD from the University of Bologna in Italy, where he was Assistant Professor between 2006 and 2017. He did postdoctoral research both in the Netherlands and as a Marie Curie Fellow at the University of Oxford in the United Kingdom. He's published more than 100 scientific papers on various astrophysical topics, and he is co-author of a textbook, *Introduction to Galaxy Formation and Evolution*, published by Cambridge University Press. He is a recipient of the Friedrich Wilhelm Bessel prize of the Alexander von Humboldt Foundation, and of course also a receiver of the award of our George Darwin Lectureship for this year. It gives me great pleasure to ask Filippo to give us his lecture.

Professor Filippo Fraternali. In our current cosmological picture, galaxies form out of two ingredients: gas and dark matter, with the latter still not directly detectable. Given that dark matter is the most abundant matter component in the Universe, it provides most of the gravity, but it is the gas that eventually produces the variety of beautiful structures that we observe with our telescopes. In general terms, all galaxies are thought to form and evolve as a consequence of the accumulation of gas at the centres of their dark-matter halos, but how this process, called gas accretion, takes place is still a matter of considerable debate. The main consequence of gas accretion into galaxies is the formation of stars in regions where the gas reaches the highest densities. This produces yet another key process that we call stellar or supernova feedback that, in turn, modifies the properties of the surrounding gas and of the gas accretion itself.

The way in which star-forming (disc) galaxies like our Milky Way gather their gas is a mechanism called 'fountain accretion', and it is ultimately powered by supernova feedback in galaxy discs. The idea is that any sizeable galaxy, after its early formation, ends up being surrounded by a hot gaseous halo that, due to the long cooling time, cannot easily accrete onto the disc. However, supernova explosions continuously eject cold and chemically enriched gas from the disc into the surroundings, and this cold material mixes with the hot halo gas making it condense very rapidly. As the ejected gas comes back to the disc (galactic-fountain cycle) it also brings condensed gas, which constitutes fresh accretion for the subsequent star formation. This fountain accretion explains why spiral galaxies keep accreting gas long after the formation of a hot halo. In the Milky Way this has likely been the accretion mechanism that led to the formation of most disc stars, including our Sun.

The Chair. Thank you very much indeed for a most interesting lecture. Can we move to the questions, Louise?

Dr. Louise Alexander. The first question that I've got at the moment is about the time-scale of the developments which are being discussed. I think the point at which that question was asked was during the part where you started to talk about fountain condensation so I don't know if you can just summarize the time-scales from that.

Professor Fraternali. The typical cycle of the Galactic fountain is of the order of a few times 10^7 years. It's actually a relatively short time. One thing that I haven't specified is that in the extra-planar layer, there is roughly 10% of the cold gas present in a galaxy like the Milky Way. But to keep this layer there (meaning outside the plane), because the time-scale is relatively short, you have to have a circulation that is actually quite active. As I was saying, eight solar masses per year need to be ejected continuously from the disc of the Milky Way to maintain the extra-planar layer. I hope this answered the question.

Dr. Alexander. Thank you very much. Mike Edmunds, has a question: "Is the chemical abundance of the in-flowing accreted gas as expected? *i.e.*, a mix of primordial and disc?"

Professor Fraternali. It is difficult to say as we don't know much about the metallicity, the chemical abundance, of the hot gas that surrounds galaxies. The estimates that we have lie between 0·1 to 0·3 of the solar value, meaning that it is relatively metal poor but not extremely metal poor. This is also due to the fact that this gas is relatively close to the disc, so there is likely some pollution taking place. There is certainly a mixture of material that is coming from outside, probably most of it, and also some material coming from the disc.

Dr. Alexander. Thank you. Stephen King is asking: "Why does hot halo gas rotate more slowly than the disc? Is the accumulation of gas slowing galactic rotation?"

Professor Fraternali. In answer to the first question; the hot gas, in principle, could even not rotate at all, because it is so hot that it can be sustained by its own pressure, so that it would be in hydrostatic equilibrium. Then, from this statement you can understand that, if there is rotation, this rotation doesn't have to be the only mechanism that is keeping the gas in equilibrium and it will be lower than the rotation of the disc gas, given that the disc is instead, completely, rotationally supported. I hope this explains the first question. What was the second question?

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Dr. Alexander. "Is the accumulation of gas slowing galactic rotation?"

Professor Fraternali. This is an extremely good question. In principle, this would be a worry, but actually what is happening in our models is the following: it is true that the gas is coming down at a lower rotation with respect to the disc, but this gas is not coming down in the centre of the galaxy but at a relatively large radius, typically 10 kpc from the centre. This is very important because then even though the rotation is slower the actual specific angular momentum of the material, which is r times V, is actually higher than the angular momentum of the disc. In the end, this type of phenomenon can increase the angular momentum of the discs on long time-scales and produce the inside-out growth of discs, which is observed and expected.

Dr. Alexander. There is another part to the question that I've missed, which was: "Does the temperature of the hot halo control the rotation speed of the disc?"

Professor Fraternali. I'm not sure I understand this question, because the rotation of the disc is very much determined, effectively, by the distribution of matter. In the disc we are talking about the rotation of cold material, so that gas has very little pressure support, and its rotation balances the gravity due to the visible matter and dark matter. These two contribute to give a flat rotation curve for most of the disc extension, a rising rotation in the centre, and possibly a decrease in the outer parts although we actually never see that. I apologize if I didn't understand the question.

Dr. Alexander. I think we've probably just got time for one more question, and it comes from Belinda Wilkes: "How do you determine the accretion rate of the cold gas falling back onto the disc? Does it include original mass of cold gas in the ejected cloud and the hot gas which has been cooled and comes into the disc?"

Professor Fraternali. When I talk about the accretion rate that is coming into the disc, I mean, essentially, only the part that is condensing from the corona, which is the part that we are interested in. Because the fountain cycle is, to some extent, I don't want to say irrelevant, but let's say it is irrelevant given that the gas goes out and comes back, goes out and comes back, maybe comes back in a different place, but that's it. The galaxy may not use that gas for a little bit, as we said the time-scales are short, but then it will get back as it falls somewhere else. However the important part is the one that is cooling and coming down. That is fresh, new gas, that can then be used for the future star formation, and that is the gas accretion we are interested in. So how do we calculate it? By trying to reproduce the kinematics of the extra-planar gas, because, given that the accreting material has a relatively low rotation, you can imagine that the more you make the cooling efficient, the more the rotation of extra-planar gas will go down. With our data we can measure this efficiency, so once I'm reproducing the rotation, I have the accretion rate that I need. And the important thing is that the accretion that you need to reproduce the extra-planar gas rotation is the same that apparently we need to feed the star formation.

Dr. Alexander. Thank you very much, Filippo; unfortunately we're out of time for questions now. But it was a great talk. I'm going to hand back to Mike Edmunds now.

The Chair. Yes, thank you so much, Filippo. A clearly-explained and, I must say, beautifully illustrated and presented talk. Thank you very much indeed.

Professor Fraternali. Thank you very much and thank you everybody for listening and joining this webinar.

The Chair. I give notice that the next A&G Open Meeting of the Society will be on Friday the 12th of November.

THE DEVELOPMENT OF EXTRAGALACTIC ASTRONOMY IN THE UK AS SEEN THROUGH BRITISH PROFESSIONAL JOURNALS: AFTER HUBBLE, PART 1 — 1925–1950

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The existence of external galaxies was conclusively proven only in the mid-1920s; Hubble's first papers on the distances to M31, M33, and NGC 6822 were published during 1925[1,2]. A previous article[3] discussed papers in British journals published prior to this which, as it turned out, were actually about galaxies (outside our own). Here we consider how extra-galactic astronomy developed in the UK over the following years, again as seen in the pages of the British professional journals, primarily in *Monthly Notices of the Royal Astronomical Society*, occasionally in *Memoirs* (though there was nothing until 1955) or *Quarterly Journal of the RAS* (from 1960), and also in *The Observatory*, then, as now, carrying reports of RAS meetings amongst other things. In the first period, up to 1950, covered in this part of the review, original British contributions were sufficiently rare that we can continue to consider them on an individual basis, as in the earlier article, and we also include overseas authors publishing in *MNRAS*, as well as reports and reviews of other overseas work which appeared in the UK journals, allowing interested Fellows to keep up with the state of play in this area. (Adding the non-specialist *Nature* to the list of journals would make little difference; there were only three relevant papers by British authors over the period considered.) Part 2 will continue the review up to 1970. The definition of 'extragalactic astronomy' is, of course, somewhat negotiable; here we will include observational (as opposed to purely mathematical) cosmology, but not topics such as individual stars in the Magellanic Clouds.

1925

First, we should recap the situation at the start of the period. Hubble's first observation of a Cepheid in the Andromeda Nebula had been made in 1923 October and his results on the distances to M31 and M33 were formally announced at the 1925 January 1 AAS Meeting[4]. (In fact, a report appeared in the *New York Times* the previous November.) However, there is no mention of this break-through in the British professional journals for some months. It was first addressed by James Jeans (RAS President at the time), in a Note in April's *MN*[5], when he had to admit that "Recent results by Hubble … seem to establish the inaccuracy of estimates I made some time ago of the distances and other quantities associated with the spiral nebulae". Hubble's own work first appeared in print in Britain in May when *The Observatory*[6] republished his original *Popular Astronomy* report of the AAS-meeting talk. J. H. Reynolds, previously a strong critic of the extra-galactic theory of spiral nebulae[3], also showed some slides of the galaxies containing Hubble's Cepheids at the end of the RAS meeting in May, as reported subsequently in *The Observatory*[7]. There was no mention of extragalactic nebulae at a Special General Meeting of the RAS in July[8] despite the presence of several notable overseas astronomers, invited in the wake of the IAU Meeting in Cambridge.

1926–1930

The 1926 February RAS Council Note on nebulae[9] by Reynolds did begin

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with a substantial piece about Hubble's work on M31 and M33. There was also a discussion of Hubble's *Astrophysical Journal* paper on M33 in *The Observatory*[10] later in the year, and it is also mentioned[11] in H. H. Turner's often whimsical column in the same journal, 'From an Oxford Note-book'. However, far from inspiring extragalactic research in the UK, there were only a handful of *MN* papers on the topic over the next decade, if we exclude those which were specifically on the theory of the expanding universe.

There had been one paper in *MN* in 1926 prior to Reynolds' note, Herko Groot updating his work on the shapes and pitch angles of spiral arms in various objects[12]. Groot was a Dutch amateur[3], but we can choose to include his paper here as it would have been read by British astronomers. As for UK-based contributors in 1926, we have Jeans reprising his existing work 'On radiative viscosity and the rotation of astronomical masses', with a short digression on spirals[13] using their newly revised dimensions. The only 'extragalactic' paper *per se* was by Reynolds[14]. He was also extending previous work on the development of the arms and degree of 'stellar condensation' in spirals (*i.e.*, the surface density of detectable stars), but again now with accurate ideas of scale. Note that both the theorist Jeans and the observer Reynolds were amateurs with no official affiliations. Reynolds' RAS-Meeting talk[15] on his paper was commented on by Jeans, Arthur Eddington, the Plumian Professor in Cambridge, Turner, Savilian Professor in Oxford, and Clive Gregory, a lecturer at UCL who had earlier used Reynolds' telescope in Helwan to photograph nebulae, certainly suggesting at least some interest amongst RAS members. (Remarkably, Reynolds' telescope was the same one as was used, after its move to Mount Stromlo, by de Vaucouleurs when developing his galaxy classification scheme and by Brian Schmidt's high-*z*-supernova search team for their Nobel Prize-winning work.)

The Astronomer Royal (Frank Dyson) communicated a very brief note[16] on a Royal Observatory observation of a nova (it was actually a supernova) in M61; perhaps surprisingly he did not mention that the host was a spiral nebula. (The observation itself appears to have been made by W. H. Steavenson[17], another noted amateur observer.)

Turner again attempted to interest British astronomers in Hubble's work *via* his column in *The Observatory*[18] in 1927, as did Reynolds in a (somewhat critical) review of Hubble's classification scheme, also in *The Observatory*[19]. Hubble in fact replied[20] to his friend Mr. Reynolds, who, though an amateur, seems to have been Hubble's only serious correspondent in the UK[21]. The one contribution in *MN* also came from outside the UK: a paper by Bertil Lindblad[22], professor of astronomy and director of the observatory in Stockholm, on stellar kinematics in what we would now recognize as bulge-plus-disc systems. In the UK, this would probably have been of most interest to those, such as Eddington, who were studying the kinematics of galactic (now Galactic) stars[23]. In a somewhat throw-away line in a paper 'On liquid stars', Jeans[24] speculated that the nuclei of spirals were composed of the same fully ionized material as white dwarfs.

Hubble returned to the RAS for the meeting of 1928 February to give a talk on Cepheids and novae in M31[25], and Ernest Brown, an English mathematician at Yale and a leading expert on lunar motion, sent a contribution to *The Observatory*[26] on 'gravitational motion in a spiral galaxy' which apparently "did not succeed in producing more than an interesting analysis of an improbable model"[27]. Astronomical historian and author Hector McPherson reviewed[28] the work of Hubble, Shapley, and Lundmark on the great distances to spiral nebulae. Interestingly, Hubble and Shapley both gave talks at the British

Astronomical Association's meeting in June[29], presumably on route to the IAU General Assembly in Leiden. William Greaves (Chief Assistant at the Royal Observatory, Greenwich, and a stellar spectroscopist by trade) reported[30] on a Harvard publication describing Luyten's attempt to determine the three-dimensional space velocity of the Magellanic Clouds relative to our Galaxy.

However, the British journals were entirely void of home-grown extragalactic astronomy that year, and the next, though Reynolds supplied the latest Council Notes on Nebulae[31] in 1929, discussing the work carried out in the USA, Sweden, and also now Germany. The next, almost incidental, UK work was hidden away in a 1930 technical paper[32] by Professor John Carroll, assistant director of the Cambridge Solar Observatory, and Mr. Moss of Cambridge Scientific Instruments on a new design of photo-electric microphotometer, which could be used to determine isophotal sizes and shapes of nebulae on a photographic plate. They used NGC 3115 (the 'Spindle Galaxy') as a test object, though they do not give its identity; this was noted in Reynolds' next review[33]. Although the paper itself is outside the remit of this article, it is noteworthy that Eddington[34] appears to have been the first British astronomer to use the term 'galaxies' in its modern sense in a paper 'On the Instability of Einstein's Spherical World'.

1931–1939

1931 saw a review[35] in *The Observatory* of Harlow Shapley's book *Flights from Chaos; A Survey of Material Systems from Atoms to Galaxies* by "H.M." (almost certainly Hector McPherson). There were also reviews[36,37] of Hubble and Humason's work on extending the velocity–distance relation to include a number of clusters by using galaxy integrated magnitudes and of Lundmark's further work on novae and Cepheids in M31[38]. However, arguably, the only (minor) contribution by a British astronomer was by Reynolds[39] at the 1931 November RAS meeting, when he queried whether Eddington's attempt to determine the rate of expansion of the Universe from first principles was affected by the clearly non-uniform distribution of spiral and elliptical nebulae. The following year, Reynolds also discussed[40] Hubble's search for globular clusters around M31 and its implications.

Also in 1932, George McVittie contributed a paper[41] at the interface of theoretical cosmology and extragalactic astronomy to *MN*, analysing the formation, in an expanding universe, of condensations that would become spiral nebulae. 'Mac' McVittie had been Eddington's PhD student and at this point was an assistant lecturer at Leeds University. Bertrand Peek supplied two papers[42,43] on the formation of spiral arms, following Jeans' theory that they were thrown off the central nebulous mass by rotation. Peek, a school master, was better known as a prominent amateur observer of the planets from his own observatory in Solihull, though with a degree in mathematics from Cambridge. His RAS talk[44] on the second paper was commented on by several people who also appear elsewhere in this article; Clive Gregory (now at Mill Hill), William Greaves, and Harold Knox-Shaw (Radcliffe Observer at Oxford). Eddington reported[45] on a meeting on 'Extra-Galactic Objects', held after the IAU in Cambridge, Massachusetts, but the only British contributor was Eddington himself, discussing the expanding universe, while "P.M." (probably Philibert Melotte of the Royal Observatory) reviewed[46] Shapley and Ames' catalogue of external galaxies.

The feature of 1933 in the current context was the fact that Harold Knox-Shaw decided to give his RAS Presidential Address[47] on the subject of 'The Distances

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and Motions of the Extra-galactic Nebulae'. Knox-Shaw had undertaken much photography of nebulae when at the observatory in Helwan prior to 1924 (using the telescope funded by the ubiquitous Reynolds) but was currently involved in Oxford's stellar work. As usual, he described the work of Hubble and Humason and others in the USA but also added some work of his own, using the Shapley–Ames catalogue to recalculate the difference between the total magnitudes of nebulae and those of their brightest stars. He also obtained a new value for 'E' — now H_0 — and explored typical peculiar velocities, the possible difference between isolated and cluster nebulae, and the effects of extinction. He ended by expressing "the hope that British astronomy, to which we owe so much of the pioneer work on nebulae … may some day be able again to play its part in contributing to this fascinating branch of our science". In fact, he seems to have done as much extragalactic astronomy while preparing his presidential talk as all his contemporaries had in the past eight years!

Knox-Shaw also presented the Society's Gold Medal to V. M. Slipher, mentioning[48] his pioneering spectra of spiral nebulae, though the recipient chose to talk on planetary spectroscopy[49]. The following year's medal[50] went to Harlow Shapley. In a wide-ranging talk[51] to the RAS he included, among others, discussions of Cepheids, the extents and radial profiles of galaxies, galaxy counts, and groups and clusters of galaxies.

Reynolds was back in 1934, with an *MN* paper[52] discussing 'The spatial distribution of the extra-galactic nebulae within a radius of 4000 kiloparsecs', using angular diameter as an indicator of distance. When this was presented at the RAS[53,54], the President, Professor (Lieutenant-Colonel) F. J. M. Stratton, director of the Cambridge Solar Physics Observatory, noted that "Mr Reynolds' paper has provoked much interest on the part of Fellows". Indeed, Reynolds' talk elicited questions from Eddington, Knox-Shaw, Peek, H. H. Plaskett (the new Savilian Professor at Oxford, a solar physicist), Gregory, Gwyn Williams (also of the Cambridge SPO, who worked on stellar spectral lines), and Roderick Redman (again at the SPO, but with a strong secondary interest in galaxy photometry, as below).

Nevertheless, Reynolds still appeared to be almost on his own in the UK in producing new results[55], discussing the radial intensity profile of NGC 205 and noting its sharp central peak. Redman and Williams commented[56] on comparisons with the centres of NGC 221 and M31. Williams[57] also reviewed colour excesses in stars and noted that Hubble's counts of spirals outside the Zone of Avoidance suggested extinction but no reddening of spirals. The most advanced theoretical paper in *MN* again came from outside Britain, Lindblad[58] developing further his theory of rotating flattened discs and the production of spiral arms. He extended his work the following year, noting specific extragalactic nebulae which showed the various structures (including rings) expected in his models[59].

The next RAS Council Note[60] on Nebulae, yet again by Reynolds (who had been contributing on the topic since 1912), appeared in 1935. It is notable that all the extra-galactic work reviewed was from the USA with the exception of Knox-Shaw's presidential address and Reynolds' own paper. (The following year, Reynolds, for his presidential address[61], chose the subject of galactic nebulae instead.) The March RAS Meeting saw a discussion[62] on the age of the Universe between the leading British cosmologists of the day, Jeans, Eddington, and Arthur Milne (professor of mathematics in Oxford, who developed his own theory of 'kinematic relativity'). This included some arguments relevant to galaxies themselves, *viz*. the time-scale for the stars to reach a dynamic equilibrium given their very long mean free paths and the time needed for the primordial gas to condense into nebulae. Bart Bok[63] (Harvard) followed this up, adding, amongst other points, time-scales associated with the generation of spiral arms by tidal encounters between galaxies.

In 1936, Bill McCrea[64] reviewed work on recession velocities and noted that Sinclair Smith at Mount Wilson had shown that the range of velocities for galaxies in the Virgo Cluster implied a total mass which required a typical galaxy to be 200 times more massive than expected. McCrea, an astrophysicist who had also collaborated with Milne and McVittie on cosmological topics and was at the time at Imperial College, refers to Smith's work as "the first published study of the physical characteristics of a cluster of nebulae" (Fritz Zwicky may have disagreed!). The following year McCrea[65] reviewed Hubble's latest work on the galaxy luminosity function. There was also a lengthy review of Hubble's *Realm of the Nebulae* by the new Astronomer Royal Harold Spencer Jones[66] (who was himself mainly an expert on the motion of Solar System bodies). He described at length Hubble's various investigations and noted that Hubble still preferred 'nebulae' to the now more fashionable 'galaxies', while commenting that "The author has a good literary style, rarely possessed by American scientific writers."

A home-grown contribution was Redman's[67] 'Photographic photometry of the elliptical nebulae' which described a programme that the Solar Physics Observatory had been working on since 1931 to determine total apparent magnitudes. Plates were taken using A. A. Common's 1891 36-inch telescope and scanned with a microphotometer (see Carroll and Moss, above), with Redman estimating a (perhaps surprisingly good) limiting surface brightness of 25·3 magnitudes per square arc second. The next year, Redman and Shirley (also SPO) discussed[68] the surface photometry of M31 in some detail, demonstrating the shape and the extremely large extent at faint surface-brightness levels, making it a rare British professional paper with actual observational results on galaxies.

At the 1937 March RAS Meeting[69], F. G. Brown gave a talk on his work on inclinations of large spirals, which was commented on by Gregory and Knox-Shaw who had both published on the topic in pre-Hubble days. Brown subsequently continued his evaluation of the inclination distribution of spirals *via* their axis ratios[70], claiming evidence for systematic orientation of their planes. Francis Brown had published his two previous *MN* papers in 1912 and continued his exploration of inclination angles until 1968. His amateur status was emphasized by him giving his home address in Forest Hill at the end of his paper. Knox-Shaw[71], though, quickly published a refutation of Brown's result and the reading of Knox-Shaw's paper at the RAS[72] (by Greaves), alongside one by Redman[73], led to considerable discussion from some of the usual suspects, Reynolds, Plaskett, Gregory, and Brown himself. Brown also returned to the fray in further contributions[74,75].

MN in 1937 saw cosmological theorists Eddington[76] and McVittie[77] (now at King's College London) venture close to the boundaries of observational extragalactic astronomy, as each attempted to explain the slope of Hubble's galaxy number counts, with Hubble responding[78], as did M. Leontovski of the Astronomical Institute, Leningrad, in *The Observatory*[79]. McVittie subsequently corrected his calculation[80].

The RAS Council Report on Novae[81] (by "A.B.", who we can assume was Arthur Beer) had contained a substantial review of recent (entirely US) work on "super-novae" in external spirals and the year's final contribution was a talk at the November RAS meeting[82] by Beer on observations of the light-curve of the

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recent supernova in NGC 1003, made at Mill Hill. This garnered comments by Reynolds, Steavenson, Plaskett, Greaves, Stratton, and Milne. Beer was a well-known astronomer, writer, and broadcaster in Germany before being forced to flee Nazi persecution, and had been at Cambridge prior to moving to the University of London. Beer and Gregory[83] and Steavenson[84] later made further supernova observations.

Reynolds was back in 1938, with the latest lengthy Council Report on extragalactic nebulae[85]. Covering 1935–1937, he reviewed in turn work on 'the nature of the spectral displacements to the red' (essentially Hubble and Eddington), 'relativistic models of the extra-galactic Universe' (Hubble and McVittie), 'the distribution of the extra-galactic nebulae' (papers by Shapley and Erik Holmberg at Lund), 'the dispersion in absolute magnitudes and linear dimensions of the extra-galactic nebulae' (Redman & Shirley), and 'photo-electric magnitudes and colours of extra-galactic nebulae' (contributions by Stebbins & Whitford at Mount Wilson). These topics cropped up again in other papers in 1938. McVittie[86,87] returned to explanations for Hubble's number counts, while Redman and Shirley[88] produced a second paper on photometry, specifically radial profiles, of elliptical nebulae. From outside the UK, Lyman Spitzer[89] (who was just completing his PhD on supergiant stars at Princeton) made a contribution on the range of galaxy absolute magnitudes. Something slightly different was a note[90] in *The Observatory* reporting Horace Babcock's measurement, at Lick, of the rotation of M31 (his Berkeley PhD thesis). A further note[91] reported Shapley's discovery of 'a stellar system of a new type', *viz*. what is now known as the Sculptor Dwarf, the first low-surface-brightness dwarf spheroidal.

After the much more productive year in 1938, British astronomers contributed very little that was extragalactic in 1939. Indeed, the only paper as such was from the persevering Mr. Brown[92] who had made a study of the position angles of 355 sufficiently large galaxy images in the Horologium region, finding an excess at angles of order 30^0 compared to the perpendicular direction (a paper still cited in some recent work). Gregory[93] noted that this should be free of many of the problems that could attend measurements of inclination angles. *MNRAS* did see two interesting overseas contributions, though. Yngve Öhman[94] of Uppsala (previously a stellar spectroscopist) reported his polarization observations of a wide range of targets including the dark lanes in M31, while Holmberg[95] presented his 'interpretation of the spectroscopically observed rotations of galaxies'. "A.D.T." (David Thackeray; yet another member of Cambridge's SPO, who worked on solar and stellar emission lines) reported[96] on Humason's observation of [O II] in extragalactic nebulae. Other, anonymous, notes in *The Observatory*[97,98] discussed Zwicky's systematic searches for supernovae in nearby galaxies and clusters, and Öhman's polarization study.

1940–1945

Unsurprisingly, activity within the RAS was significantly curtailed from 1939 September, though some meetings continued to be held. At the AGM in 1940 February, the Gold Medal was awarded[99] to Edwin Hubble for "his outstanding work on the distances, velocities, distribution and nature of the extra-galactic nebulae". In the enforced absence of the recipient, the medal was handed by RAS President H. C. Plummer to the First Secretary of the American Embassy. Perhaps appropriately in the circumstances, Plummer (originator of the Plummer potential for stellar systems) was a professor at the Military College of Science in Woolwich.

The only 1940 paper of relevance here[100] was by cosmologist Geoffrey Walker, at this point a lecturer in pure mathematics at Liverpool University, who explored whether Brown's result on the inclinations of galaxies was compatible with the Cosmological Principle. (Walker had already independently devised what is now known as the Robertson–Walker metric while still a post-grad in Oxford working with Milne.)

A note in *The Observatory* spoke of things to come, however. It reported[101] on Grote Reber's follow-up of Jansky's original detection of the Galaxy at radio wavelengths, noting that "the only region of the sky apart from the Milky Way which has yet been found to produce appreciable effects is the Andromeda Nebula". In an overview of 'Astrophysics 1930–1940', Thackeray[102] noted just two extra-galactic items, the recognition of, and surveys for, supernovae and the "controversy [which] has raged over the problem of attributing the shifts to a Doppler effect in an expanding universe or to some other cause", the latter a perhaps unexpected comment from today's perspective, coming eleven years after Hubble's classic paper.

There were no extragalactic contributions at all in 1941 and in 1942 there was just one relevant report. In a general discussion of the 'Structure and Rotation of the Galaxy' at July's RAS Meeting[103] Alan Hunter, opening the session, noted that the measured dimensions of extragalactic systems had recently grown larger and were therefore more comparable to those of our Galaxy. Hunter, head of Astrometry and Astrophysics at the Royal Observatory at Greenwich, was an expert in stellar distance measurements. RO's director, Astronomer Royal Spencer Jones, then talked on 'The rotation of extra-galactic nebulae and their internal distribution of mass'. He reviewed the recent work on rotation curves, which originated entirely from the US (though Babcock had made use of Redman & Shirley's photometry in order to deduce a high mass-to-light ratio for the outer parts of M31).

Spencer Jones also wrote the obituary for RAS Associate H.D. Curtis in 1943[104]. Interestingly for the mythology of the subject, though Curtis' arguments in favour of the extragalactic nature of spirals are recalled, his supposedly key 'Great Debate' with Shapley in 1920 is not mentioned. (Nor is it in his obituary in *Astrophysical Journal*.)

The one article[105] keeping UK astronomers up to date with the field was by McVittie who reviewed 16 papers by Shapley and co-workers at Harvard between 1939 and 1942 published under the general title of 'Galactic and Extragalactic Studies'. The first seven were on Cepheids, the next five on 'investigations of the structure of certain individual nebulae' (including Shapley's new Sculptor and Fornax dwarf systems, and a paper on densitometer measures of 112 spiral and spheroidal nebulae), and the final four on the large-scale distribution of nebulae (both on the sky and as a function of magnitude, the latter being one of McVittie's particular interests). McVittie was at this time head of the Meteorological Centre at Bletchley Park, breaking coded enemy weather forecasts and *inter alia* locating the sources of the reports, which often turned out to be U-boats. The following year, similar ground was covered in Reynolds review[106] of Shapley's famous book *Galaxies*.

During the war, astronomical contacts with other countries had necessarily been interrupted. A Committee for the Distribution of Astronomical Literature (C.D.A.L.) had therefore been formed by the American Astronomical Society to attempt to remedy this. Summaries of their *Bulletins* were given in *The Observatory*, and No. 13[107] covered Swedish papers, including two by Lindblad, continuing his work on spiral structure and one by Öhman on polarization in

M31. Recent observations, including Öhman's, as they related to Lindblad's theory of spiral structure, were also noted at the end of an RAS Council report on stellar dynamics by Subrahmanyan Chandresekhar[108]. Chandrahsekhar had been at Yerkes since leaving Cambridge, though he worked at the Ballistic Research Laboratory during the war. Stellar dynamics was just one of his many interests in the application of mathematics to astronomical problems.

Another sign of the times — and of general interest in extra-galactic astronomy — was a report in *The Observatory*[109] of McVittie's lecture 'The Spiral Nebulae' as part of a series 'Popular Astronomy for the Forces'. The overworked McVittie[110] also wrote a note on the 'Resolution of nebulae', summarizing Baade's work on M31 and its companions which led to his discrimination of Population I and Population II stars. Another note[111], by "A.H." (presumably Alan Hunter who, like McVittie, was an editor of *The Observatory*) described Reber's latest work on "cosmic static" which had found a radio maximum in Cygnus amongst others; then thought to be associated with a spiral arm, this was later identified as the first radio galaxy, Cygnus A.

The RAS held another discussion on extragalactic nebulae at their 1945 June meeting[112]. Hunter again gave the introductory talk, reminding fellows of the classification system with respect to how well the nebulae could be resolved into stars with the 100-inch telescope. Reynolds gave a history of photographic imaging of nebulae (he had himself been involved in this since 1909) and rather critically discussed recent work on their distribution on the sky and their measured magnitudes. This scepticism led to responses from the (relatively) younger generation of Plaskett (the President), Milne, Greaves, Dingle, and Smart. Herbert Dingle, professor of Natural Philosophy at Imperial College was another stellar spectroscopist turned cosmologist, who argued with both Milne and Eddington. William Smart was an expert in stellar kinematics and at this point Regius Professor of Astronomy in Glasgow. McVittie then talked on 'The Local Group of Nebulae', giving a description of the 13 then-known members. Plaskett, Dingle, Hunter, and Milne this time asked the questions. The final talk of the day was by a perhaps slightly surprising contributor, Fred Hoyle, who had just returned to Cambridge after his wartime work on radar and was known at the time for his papers on stellar structure and evolution. He started his talk in what might be considered characteristic fashion, though, remarking that "many of the older beliefs concerning the structure of extra-galactic nebulae … may be in need of considerable revision". He then presented his take on Baade's discovery of different stellar populations in bulges and discs and of the insignificance of spiral arms in photographs taken at infrared wavelengths.

Hoyle subsequently had four successive papers in *MN*[113] on 'The structure of disk-shaped extragalactic nebulae'. In these he introduced his new framework for the structure and kinematics of stellar systems by folding in a dominant non-stellar disc component (as required by the rotation curves; he assumed that this was largely hydrogen plus some dust). He then made a number of inferences such as the low temperatures required for star formation to take place (of order 10 K), the thinness of the gas disc compared to the stellar disc (thus requiring a mechanism to generate vertical peculiar velocities in older stars; he suggested interactions with passing globular clusters), and the shearing of regions of high-mass star formation by differential rotation to form spiral arms. Much of the latter three papers are substantially concerned with star formation and accretion (including accretion of 'internebular' material) in such a model. Hoyle also made a point of using the capitalized 'Galaxy' for our system. His talk at the RAS summarizing the four papers[114] elicited comments from

Reynolds, Milne, Steavenson, Plaskett, Gregory, Hunter, Frederick Hargreaves, and Mervyn Ellison. Hargreaves was an amateur optical instrumentalist who mainly undertook planetary observations. Ellison was also then an amateur, mostly interested in solar observations, but obtained an appointment at the ROE the following year.

1946–1950

In 1946, Bok provided a report to the RAS[115] on 'The time-scale of the Universe', one aspect of which was the time required for a cluster of galaxies to evaporate, Bok being unwilling to accept the large masses required for equilibrium. All the work reviewed was, like Bok, from US observatories. Continuing the theme of contributions by overseas experts, the RAS George Darwin Lecture[116] was given by Jan Oort, recently restored to his professorship in Leiden at the end of the war. In an exposition of 'Some phenomena connected with interstellar matter', Oort included a comparison with absorption effects seen in other galaxies and the lack of it in ellipticals — "one might venture to suggest that the absence of highly luminous stars in elliptical nebulae is connected with the absence of interstellar gas and smoke". Oort concurred with Hoyle (above) that spirals must have a dominant thin gaseous disc.

Returning to home-grown papers, Lt.-Col. Kenneth Edgeworth followed Hoyle with a set of three papers[117] examining the process of the condensation of stars in a rotating disc. Edgeworth was a retired military officer and economist who had been an FRAS since 1902 and is best known for proposing what is now the Edgeworth–Kuiper belt of trans-Neptunian dwarf planets. Hoyle, Gregory, Milne, and Robert Atkinson (Chief Assistant at the RO, a stellar astrophysicist turned instrumentalist) asked questions following his later talk[118] at the RAS.

Alan Fletcher, an applied mathematics lecturer at Liverpool University, recalculated 'The number of galaxies per unit volume' with an improved statistical method[119], at the suggestion of his colleague A. G. Walker (see earlier). Walker himself also discussed the brightnesses and counts of galaxies in the cosmology of kinematic relativity[120]. Milne[121] addressed the problem of spiral arms in his kinetic theory of gravitation, going back to Jeans' idea of "ejection from a fixed point near the centre of the nebula". Unsurprisingly Hoyle had some comments[122] when Milne talked on this at the RAS. (There was also a review[123] by Dingle of a book by Martin Johnson, a physics professor in Birmingham, which discussed Milne's model and a comment on this by Walker[124].) Hoyle was also back again, this time attempting to calculate[125] the intensity of cosmic rays if they were produced by supernovae (given the SN rate per galaxy and the number density of galaxies) and compare it to the flux observed at the Earth.

The RAS also saw a major discussion[126], at an 'Additional Ordinary Meeting' in 1946, on the construction of a large telescope (possibly a 72-inch similar to those in South Africa and Canada) to be sited in southern England, a project with which RAS President Plaskett was much involved. Greaves, now the Astronomer Royal for Scotland, discussed the three most important prospective observational areas, the third being "the universe of extragalactic nebulae", though he suggested that a large-aperture Schmidt might be more suitable for galaxy photometry.

Though 1947 was a very quiet year for British extragalactic astronomy, Hoyle[127] was still active in this area, producing criteria for the condensation of stars in galaxies which implied that elliptical galaxies and nuclei (bulges) of spirals should be "almost entirely condensed" (*i.e.*, all stars) but discs should

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be "largely uncondensed" (large fraction of gas). He also used the theoretical lifetimes of stars as a function of mass to deduce that galaxies had ages around 5×10^9 years. His corresponding talk at the RAS[128] brought forth the usual argument with Milne. (Though not strictly within this article's remit, Milne appears to have made the first British contribution on galaxies to a US professional journal when he published a paper on spiral arm shapes in *ApJ* in 1947[129].)

The year 1948 began with Hermann Bondi[130] reviewing 'Cosmology', the section on 'Observational Evidence' covering the main questions in observational cosmology at the time, in particular the deduction of distance from apparent magnitude or the direct prediction of apparent magnitude from the cosmological models (including factors such as the 'K term' and possible evolution), and the estimation of the mean density of the Universe. Bondi also commented[131] on McVittie's recent work, emphasizing further the uncertainties. (Interestingly an incorrect value of Hubble's constant was never mentioned as a possible cause of some numerical inconsistencies.) Bondi and Gold[132] subsequently examined the same observables in their new 'Steady State' model where there is no possibility of a systematic change of galaxy luminosities with redshift. (Interestingly, they made a point of refuting Hoyle's upcoming steady-state paper!) Bondi at this point was a maths lecturer in Cambridge while Tommy Gold, like Bondi a Fellow at Trinity College, had been working at the Cambridge Zoology Laboratory. Hoyle's paper[133] appeared the following month but had rather little observational content apart from an estimate of the required mean density and the maximum age of observable galaxies.

The RAS Gold Medal that year went to Lindblad, and in his George Darwin Lecture he reviewed[134] the 'Dynamics of stellar systems', noting that a complete theory, extrapolated from the study of our Galaxy, should be able to explain all the structural features seen in all types of spiral galaxy. Milne also produced two more papers[135] on 'spiral orbits', considering first their stability and then the effect of more extended mass distributions. He presented the papers at the Edinburgh meeting[136] of the RAS, the first one held outside London, with comments and queries from Smart, Sir Edmund Whittaker (a noted mathematical physicist, professor in Edinburgh since 1912), and, of course, Hoyle.

A perhaps less likely lecturer in the UK was CalTech's Fritz Zwicky who gave the Halley Lecture[137] at Oxford, talking on his favourite topic of 'Morphological Astronomy'. It should be remembered that for Zwicky, 'morphological' referred to a way of thinking, not just the description of objects. The inferences he drew from observations were relevant to many areas we still recognize today, such as the structure and dynamics of galaxy clusters, the luminosity function of galaxies, and surveys for supernovae.

October's issue of *The Observatory* contained a report[138] on the IAU Meeting in Zurich, including considerable new work covered by Commission 28 (Extragalactic Nebulae). All of it emanated from the USA, though McVittie was quoted in the discussion on theoretical interpretation.

After a relative high, extragalactic work reported in UK journals was again very sparse in 1949 but it did at least contain rare observational contributions, even if one author didn't realize it. David Evans[139] had obtained red and blue surface photometry of NGC 5128 (now better known as Cen A) at the Radcliffe Observatory in Pretoria, finding it to have a roughly inverse-square profile away from the obscuring material. He inferred a scattering nebula around a central luminous source hidden by the dust lane and that it seemed "hardly possible … to classify it as extra-galactic". In a subsequent paper, Evans and Thackeray[140] (the latter now also in Pretoria) established that several southern objects thought to be planetary nebulae were in fact galaxies.

An interesting correspondent to *The Observatory*[141] was Gérard de Vaucouleurs, then still in Paris, who suggested a method for determining whether the spiral arms in M31 were leading or trailing, based on the fact that stars in the 'front' arm should be 3% nearer than those on the far side.

The only other article was the report[142] on a symposium in Paris on 'Hydrodynamical Problems concerning Masses of Cosmical Dimension' which had attracted some well-known names. While most of the talks and discussion concentrated on clouds in our Galaxy, Hoyle considered the generation of the rotation of galaxies by "intergalactic gravitational couples" (others thought it was a result of turbulence). Ray Lyttleton, the writer of the article, was a maths lecturer in Cambridge who wrote numerous papers on accretion with Hoyle.

The 1950 Gold Medal was won by Joel Stebbins of Mount Wilson. In his George Darwin Lecture[143] he covered the whole range of photoelectric photometry, including multi-wavelength observations of M31 and other nearby galaxies as well as more distant ones in clusters, noting that ellipticals became redder with redshift. (In his address on the award of the medal[144], Smart also noted that Stebbins had found a very small dispersion in colour for nearby ellipticals.) McVittie[145] then made a theoretical calculation of the colour index as a function of cosmological redshift, including the effects of spectral shape and look-back time. Although technically beyond our time limit, McVittie gave a talk on this work the following year[146], in the 'out of town' summer meeting in Exeter, which was commented on by Dingle (now the RAS President), Bondi, Smart, and Hoyle.

An anonymous Note[147] in *The Observatory* recorded that Harrington and Wilson, using the 48-inch Schmidt on Palomar Mountain, had discovered two new dwarf stellar systems in Leo: "one of these … is the smallest ever found". In addition, Thackeray[148] had carried out a survey for variable stars in the Sculptor dwarf, finding the same relationship between period and amplitude as in the globular cluster Omega Centauri.

A paper that broke new ground was by Martin Ryle, Francis Graham Smith, and Bruce Elsmore[149] from the recently founded Cambridge radio astronomy group at the Cavendish Lab. Their interferometric survey of "radio stars" showed no concentration to the Galactic Plane, suggesting that they were either nearby or were outside the Galaxy. Though they preferred the first option in general, they did find that the positions of a handful of their weaker sources were close to nearby spirals. John Bolton reported at the RAS[150] on the identification, at the Radiophysics Laboratory in Sydney, of radio sources associated with M87 and NGC 5128.

To end with some symmetry to the beginning of this article, Edwin Hubble attended the same 1950 August RAS Meeting and reported[150] on early results with the new 200-inch telescope on Palomar Mountain. In particular he showed slides demonstrating the resolution that could be achieved on nearby galaxies, including the dwarf NGC 147, and the huge numbers of faint galaxies visible "at the limit of penetration" (estimated to be magnitude 23) in areas away from the Galactic Plane.

Summary

It is clear from the above that UK astronomers made relatively few original contributions to extragalactic astronomy up to 1950, though they were kept informed of advances made elsewhere (primarily the USA). Opportunities for front-rank observational studies were limited by a lack of large telescopes, so theoretical work, including cosmology, predominated. While Hubble and his colleagues had had the 100-inch at Mount Wilson since 1917, the RO obtained a telescope as large as 36-inch only in 1934[151]. (Notice that this was still only half the diameter of Lord Rosse's Leviathan of Parsonstown from the previous century.) In terms of people, over the 25 years, 26 British astronomers contributed to 47 actual papers (as opposed to reviews). Nearly half of these (22) were between 1945 and 1950 (seven of them coming from Fred Hoyle). Thirteen additional British astronomers supplied reports and notes and another half a dozen asked questions at RAS Meetings. Of the paper authors, six were amateurs, with the 20 professionals split nearly equally between observatory staff and university academics (and all were male). In terms of places, Cambridge clearly predominated with 12 of the 20 professionals, with a few from Oxford (plus Pretoria), London, Liverpool, and Leeds. Notably there were no contributions from the RO except reviews and notes.

Appropriately, the last two contributions noted above, on the new radio astronomy and on the technological leap in telescope size in optical astronomy, were the sign of things to come in the next generation of extragalactic astronomy which will be covered in the second part of this article.

References

(1) E. P. Hubble, *PA*, **33**, 252, 1925.
(2) E. P. Hubble, *ApJ*, **62**, 409, 1925.
(3) S. Phillipps, *The Observatory*, **140**, 185, 2020.
(4) Report on 33rd Meeting of the AAS, *PA*, **33**, 158, 1925.
(5) J. H. Jeans, *MNRAS*, **85**, 531, 1925.
(6) E. P. Hubble, *The Observatory*, **48**, 139, 1925 (reprinted from reference 1).
(7) RAS Meeting Report, *The Observatory*, **48**, 161, 1925.
(8) Report of RAS Special Meeting, *MNRAS*, **85**, 901, 1925.
(9) Council Note (J. H. Reynolds), *MNRAS*, **86**, 257, 1926.
(10) Notes, *The Observatory*, **49**, 311, 1926.
(11) From an Oxford Note-Book, *The Observatory*, **49**, 348, 1926.
(12) H. Groot, *MNRAS*, **86**, 146, 1926.
(13) J. H. Jeans, *MNRAS*, **86**, 328, 1926.
(14) J. H. Reynolds, *MNRAS*, **87**, 112, 1926.
(15) RAS Meeting Report, *The Observatory*, **50**, 1, 1927.
(16) Note, *MNRAS*, **86**, 631, 1926.
(17) W. H. Steavenson, *MNRAS*, **87**, 568, 1927.
(18) From an Oxford Note-Book, *The Observatory*, **50**, 98, 1927.
(19) J. H. Reynolds, *The Observatory*, **50**, 185, 1927.
(20) E. P. Hubble, *The Observatory*, **50**, 276, 1927.
(21) J. H. Reynolds, *The Observatory*, **50**, 308, 1927.
(22) B. Lindblad, *MNRAS*, **87**, 420, 1927.
(23) Council Note (A. S. Eddington), *MNRAS*, **88**, 329, 1927.
(24) J. H. Jeans, *MNRAS*, **87**, 720, 1927.
(25) E. P. Hubble, *The Observatory*, **51**, 108, 1928.
(26) E. W. Brown, *The Observatory*, **51**, 277, 1928.
(27) F. Schlesinger & D. Brouwer, *NAS Biographical Memoirs*, **XXI**, 1939.
(28) H. McPherson, *The Observatory*, **51**, 315, 1928.
(29) British Astronomical Association Meeting, *The Observatory*, **51**, 261, 1928.
(30) Publications, *The Observatory*, **51**, 226, 1928.
(31) Council Note (J. H. Reynolds), *MNRAS*, **89**, 396, 1929.
(32) J. A. Carroll & E. B. Moss, *MNRAS*, **91**, 191, 1930.
(33) Council Note (J. H. Reynolds), *MNRAS*, **91**, 416, 1931.
(34) A. S. Eddington, *MNRAS*, **90**, 668, 1930.
(35) Publications, *The Observatory*, **54**, 145, 1931.
(36) Notes, *The Observatory*, **54**, 223, 1931.
(37) Council Note (J. H. Reynolds), *MNRAS*, **92**, 347, 1932.

(38) Council Report, *MNRAS*, **92**, 330, 1931.
(39) RAS Meeting Report, *The Observatory*, **54**, 313, 1931.
(40) J. H. Reynolds, *The Observatory*, **55**, 301, 1932.
(41) G. C. McVittie, *MNRAS*, **92**, 500, 1932.
(42) B. M. Peek, *MNRAS*, **92**, 707, 1932.
(43) B. M. Peek, *MNRAS*, **93**, 152, 1932.
(44) RAS Meeting Report, *The Observatory*, **56**, 1, 1933.
(45) A. S. Eddington, *The Observatory*, **55**, 301, 1932.
(46) Publications, *The Observatory*, **55**, 316, 1932.
(47) H. Knox-Shaw, *MNRAS*, **93**, 304, 1933.
(48) President's Speech (H. Knox-Shaw), *MNRAS*, **93**, 476, 1933.
(49) V. M. Slipher, *MNRAS*, **93**, 657, 1933.
(50) President's Address (H. Knox-Shaw), *MNRAS*, **94**, 592, 1934.
(51) H. Shapley, *MNRAS*, **94**, 791, 1934.
(52) J. H. Reynolds, *MNRAS*, **94**, 196, 1934.
(53) RAS Meeting Report, *The Observatory*, **57**, 41, 1934.
(54) Correspondence, *The Observatory*, **57**, 68, 1934.
(55) J. H. Reynolds, *MNRAS*, **94**, 519, 1934.
(56) RAS Meeting Report, *The Observatory*, **57**, 141, 1934.
(57) E. G. Williams, *The Observatory*, **57**, 128, 1934.
(58) B. Lindblad, *MNRAS*, **95**, 12, 1934.
(59) B. Lindblad, *MNRAS*, **95**, 663, 1935.
(60) Council Note (J. H. Reynolds), *MNRAS*, **95**, 410, 1935.
(61) J. H. Reynolds, *MNRAS*, **96**, 393, 1935.
(62) RAS Meeting Report, *The Observatory*, **58**, 101, 1935.
(63) B. J. Bok, *The Observatory*, **59**, 76, 1936.
(64) Notes, *The Observatory*, **59**, 60, 1936.
(65) W. H. McCrea, *The Observatory*, **60**, 23, 1937.
(66) Publications, *The Observatory*, **59**, 337, 1936.
(67) R. O. Redman, *MNRAS*, **96**, 588, 1936.
(68) R. O. Redman & E. G. Shirley, *MNRAS*, **97**, 416, 1937.
(69) RAS Meeting Report, *The Observatory*, **60**, 85, 1937.
(70) F. W. Brown, *MNRAS*, **98**, 218, 1938.
(71) H. Knox-Shaw, *MNRAS*, **98**, 587, 1938.
(72) RAS Meeting Report, *The Observatory*, **61**, 173, 1938.
(73) Correspondence, *The Observatory*, **61**, 216, 1938.
(74) Correspondence, *The Observatory*, **61**, 250, 1938.
(75) F. G. Brown, *MNRAS*, **99**, 14, 1938.
(76) A. S. Eddington, *MNRAS*, **97**, 156, 1937.
(77) G. C. McVittie, *MNRAS*, **97**, 163, 1937.
(78) E. P. Hubble, *MNRAS*, **97**, 506, 1937.
(79) M. Leontovski, *The Observatory*, **60**, 239, 1937.
(80) Correspondence, *The Observatory*, **60**, 170, 1937.
(81) Council Note, *MNRAS*, **97**, 355, 1937.
(82) RAS Meeting Report, *The Observatory*, **60**, 305, 1937.
(83) A. Beer & C. C. L. Gregory, *MNRAS*, **98**, 216, 1938.
(84) W. H. Steavenson, *MNRAS*, **98**, 673, 1938.
(85) Council Report (J. H. Reynolds), *MNRAS*, **98**, 334, 1938.
(86) G. C. McVittie, *MNRAS*, **98**, 384, 1938.
(87) G. C. McVittie, *The Observatory*, **61**, 209, 1938.
(88) R. O. Redman & E. G. Shirley, *MNRAS*, **98**, 613, 1938.
(89) L. Spitzer, *The Observatory*, **61**, 104, 1938.
(90) Notes, *The Observatory*, **61**, 304, 1938.
(91) Notes, *The Observatory*, **61**, 254, 1938.
(92) F. G. Brown, *MNRAS*, **99**, 534, 1939.
(93) RAS Meeting Report, *The Observatory*, **62**, 113, 1939.
(94) Y. Öhman, *MNRAS*, **99**, 624, 1939.
(95) E. Holmberg, *MNRAS*, **99**, 650, 1939.
(96) Notes, *The Observatory*, **62**, 26, 1939.
(97) Notes, *The Observatory*, **62**, 195, 1939.
(98) Notes, *The Observatory*, **62**, 305, 1939.
(99) Address (H. C. Plummer), *MNRAS*, **100**, 342, 1940.
(100) A. G. Walker, *MNRAS*, **100**, 623, 1940.
(101) Notes, *The Observatory*, **63**, 292, 1940.
(102) A. D. Thackeray, *The Observatory*, **63**, 311, 1940.

(103) RAS Meeting Report, *The Observatory*, **64**, 283, 1942.
(104) Obituary Notices, *MNRAS*, **103**, 73, 1943.
(105) Publications, *The Observatory*, **65**, 102, 1943.
(106) Publications, *The Observatory*, **65**, 222, 1943.
(107) Notes, *The Observatory*, **65**, 152, 1944.
(108) Council Report (S. Chandrasekhar), *MNRAS*, **105**, 124, 1945.
(109) Popular Astronomy for the Forces, *The Observatory*, **66**, 26, 1945.
(110) Notes, *The Observatory*, **66**, 35, 1945.
(111) Notes, *The Observatory*, **66**, 92, 1945.
(112) RAS Meeting Report, *The Observatory*, **66**, 99, 1945.
(113) F. Hoyle, *MNRAS*, **105**, 287 *et seq.*, 1945.
(114) RAS Meeting Report, *The Observatory*, **66**, 194, 1946.
(115) Council Report (B. J. Bok), *MNRAS*, **106**, 61, 1946.
(116) J. H. Oort, *MNRAS*, **106**, 159, 1946.
(117) K. E. Edgeworth, *MNRAS*, **106**, 470 *et seq.*, 1946.
(118) RAS Meeting Report, *The Observatory*, **68**, 9, 1948.
(119) A. Fletcher, *MNRAS*, **106**, 121, 1946.
(120) A. G. Walker, *The Observatory*, **66**, 285, 1946.
(121) A. E. Milne, *MNRAS*, **106**, 180, 1946.
(122) RAS Meeting Report, *The Observatory*, **66**, 269, 1946.
(123) Publications, *The Observatory*, **66**, 187, 1945.
(124) A. G. Walker, *The Observatory*, **66**, 215, 1946.
(125) F. Hoyle, *MNRAS*, **106**, 384, 1946.
(126) RAS Meeting Report, *The Observatory*, **66**, 308, 1946.
(127) F. Hoyle, *MNRAS*, **107**, 334, 1947.
(128) RAS Meeting Report, *The Observatory*, **67**, 211, 1947.
(129) E. A. Milne, *ApJ*, **106**, 137, 1947.
(130) Council Report, *MNRAS*, **108**, 104, 1948.
(131) Correspondence, *The Observatory*, **68**, 111, 1948.
(132) H. Bondi & T. Gold, *MNRAS*, **108**, 252, 1948.
(133) F. Hoyle, *MNRAS*, **108**, 372, 1948.
(134) B. Lindblad, *MNRAS*, **108**, 214, 1948.
(135) E.A. Milne, *MNRAS*, **108**, 309 and 316, 1948.
(136) RAS Meeting Report, *The Observatory*, **68**, 209, 1948.
(137) F. Zwicky, *The Observatory*, **68**, 121, 1948.
(138) The International Astronomical Union, *The Observatory*, **68**, 161, 1948.
(139) D. S. Evans, *MNRAS*, **109**, 94, 1949.
(140) D. S. Evans & A. D. Thackeray, *MNRAS*, **110**, 429, 1950.
(141) Correspondence, *The Observatory*, **69**, 150, 1949.
(142) The Paris Symposium, *The Observatory*, **69**, 222, 1949.
(143) J. Stebbins, *MNRAS*, **110**, 416, 1950.
(144) President's Address (W. M. Smart), *MNRAS*, **110**, 179, 1950.
(145) G. McVittie, *MNRAS*, **110**, 590, 1950.
(146) RAS Meeting Report, *The Observatory*, **71**, 174, 1951.
(147) Notes, *The Observatory*, **70**, 163, 1950.
(148) A. D. Thackeray, *MNRAS*, **70**, 144, 1950.
(149) M. Ryle, F. G. Smith & B. Elsmore, *MNRAS*, **110**, 508, 1950.
(150) RAS Meeting Report, *The Observatory*, **70**, 129, 1950.
(151) The Opening of the Yapp Telescope at Greenwich, *The Observatory*, **57**, 218, 1934.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 8: THE DOUBLY-ECLIPSING QUADRUPLE STAR SYSTEM V498 CYGNI

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V498 Cyg is an early-B-type binary known to show eclipses on a period of 3·48 d, and two sets of spectral lines. We present the discovery of a second set of eclipses, on a 1·44-d period, in the light-curve of this object from the *Transiting Exoplanet Survey Satellite* (*TESS*). We develop a model of the light-curve simultaneously to fit the properties of both eclipsing binaries and apply this to the *TESS* observations. We are able to fit the light-curve of the fainter system well, but the light-curve fit for the brighter system is unable to reproduce either its asymmetric primary eclipse or its changing light-curve shape. The available eclipse-timing measurements are extremely scattered so we determine orbital ephemerides based only on the *TESS* data. We infer the physical properties of all four stars, estimating the masses of the components of the brighter binary to be 10 $M_\odot$ and 11 $M_\odot$, and of the fainter binary to be 6·5 $M_\odot$ and 3·5 $M_\odot$. The properties of the system may be reliably determined in future by obtaining radial-velocity measurements of the component stars.

Introduction

Detached eclipsing binary stars (dEBs) are a vital source of directly-measured properties of normal stars against which our understanding of stellar physics can be examined[1–3]. High-mass stars are known to be found predominantly in systems with a high incidence of binarity or higher-order multiplicity[4,5]. The binary fraction, plus the distributions of mass ratio and orbital eccentricity, is useful in understanding the formation processes of single and binary stars[6–9].

As a small fraction of stellar systems are quadruple or of higher multiplicity, it is possible to observe two dEBs in one system. Although a few have been discovered from ground-based observations (V994 Her[10], CzeV343[11], V482 Per[12]), the great majority have only recently been identified using data from the current generation of space-based photometric surveys such as *Kepler*, *CoRoT*, and *TESS*, including KIC 4247791[13], KIC 4150611[14], EPIC 219217635[15], TIC 278956474[16], BG Ind[17], TIC 454140642[18], and BU CMi[19]. The system TIC 168789840 has been found to contain *three* dEBs with short orbital periods (1·57, 8·21, and 1·31 d) and strikingly similar primary (each 1·2–1·3 $M_\odot$) and secondary (each approximately 0·6 $M_\odot$) components. A detailed review of the impact of space-based photometry on binary-star science can be found in Southworth[20].

As the multiplicity of massive stars is higher, it is to be expected that some such systems might host two or more eclipsing binaries. However, to our knowledge, the earliest spectral type found in the systems mentioned above is B8 V. In this work we present the discovery that V498 Cyg shows two sets of eclipses, with periods of 3·48 and 1·44 d. The two stars in the brighter dEB are of an early-B spectral type, making this system possibly the most massive doubly-eclipsing binary known.

TABLE I

Basic information on V498 Cyg

Property	*Value*	*Reference*
Henry Draper designation	HD 229179	21
Tycho designation	TYC 3152-577-1	22
Gaia EDR3 designation	2061233871414590208	23
Gaia EDR3 parallax	0·591 ± 0·016 mas	23
TESS designation	TIC 13968858	24
B_T magnitude	10·934 ± 0·057	22
V_T magnitude	9·977 ± 0·029	22
J magnitude	7·657 ± 0·019	25
H magnitude	7·447 ± 0·017	25
K_S magnitude	7·318 ± 0·020	25
Spectral type	B1·5 V	26

V498 Cygni

Some basic information on V498 Cyg is given in Table I. The B_T and V_T magnitudes are from the Tycho-2 catalogue[22] and are the averages of thousands of measurements covering all orbital phases. The JHK_S magnitudes are single-epoch and their orbital phases cannot be established precisely (see below) so should be read as indicative values only.

The literature on V498 Cyg is sparse. Hiltner[27] assigned a spectral classification of B1:III:, inconveniently given with designation BD +38°4054 and its HD number missing from the relevant column. The variability of the system was discovered by Hoffmeister[28] and described as short-period. Quite a few studies have presented times of minimum light or light-curves of often limited quality[29–35].

The only substantive analysis of the system is by Zakirov & Eshankulova[36], who presented extensive photometry in the Johnson *UBVR* system. They found clear evidence for orbital eccentricity: the secondary eclipse occurred at phase 0·526 and its duration differed from that of the primary (0·18 *versus* 0·23 in phase units). They also found that "the light curves have some irregularities and the shape of the curves is unstable in all spectral bands" and tentatively attributed this to the presence of a third body.

V498 Cyg originally came to the author's attention due to a paper by Lacy[26] which reported the discovery of two sets of spectral lines. Lacy assigned a spectral type of B1·5 V to the system and stated that the depths and widths of the lines from the two stars were similar. The dwarf spectral classification is more consistent with the expected sizes of the stars (the system is detached and has a 3·48-d period) than the previous classification as a giant, so should be preferred. V498 Cyg was included in a systematic trawl through a list of interesting eclipsing binaries with light-curves in the *TESS* database, and it was immediately noticed that two sets of eclipses were present. The analysis of these data is reported below. Whilst this work was being performed, Eisner *et al.*[37] independently discovered the multi-eclipsing nature of the system but did not present any analysis.

Observational material

V498 Cyg has been observed on three occasions by the NASA *TESS* satellite[38]: in sectors 14 (2019/07/18 to 2019/08/15), 15 (2019/08/15 to 2019/09/11), and 41 (2021/07/23 to 2021/08/20); and a fourth visit is planned (sector 55 in 2022 August). In each case the observations lasted for approximately 27 d and were continuously sampled at a cadence of 120 s except for mid-sector pauses for the data to be downlinked to Earth.

The data were downloaded from the MAST archive* and converted to relative magnitude. Observations with a QUALITY flag of less than 5000 were retained as they appeared to be reliable; restricting to a QUALITY of zero would cause the loss of several thousand datapoints. We used the simple aperture photometry (SAP) version of the *TESS* data[39] as it is the more suitable for stars with strong intrinsic brightness variations. The light-curves are shown in Fig. 1.

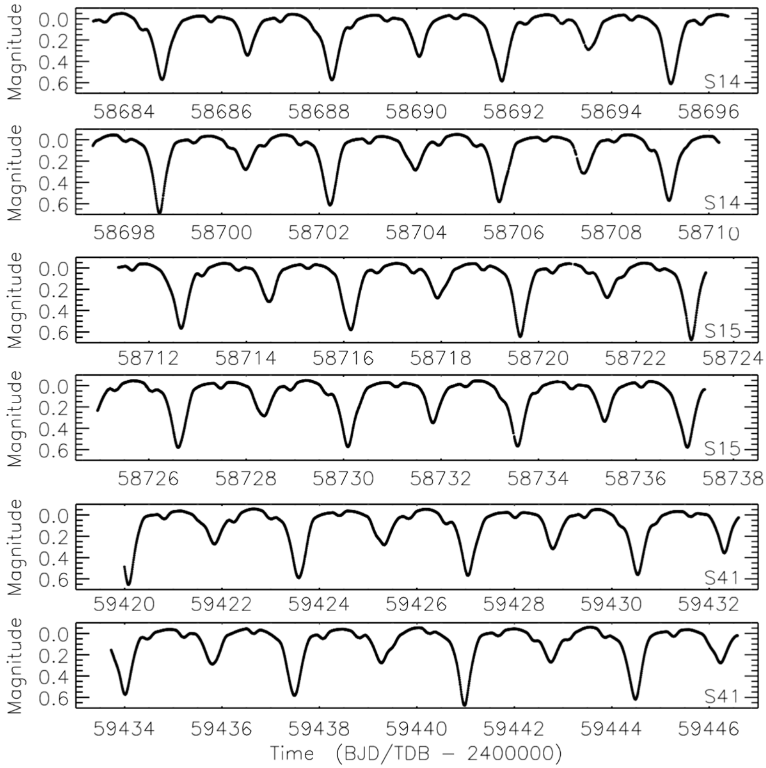

FIG. 1

TESS short-cadence SAP photometry of V498 Cyg from sectors 14, 15, and 41 (labelled). Each panel contains half a sector of data, from either before or after the mid-sector gap in observations. The flux measurements have been converted to relative magnitude and rectified to zero magnitude by subtraction of low-order polynomials. The observations have also been binned by a factor of five before plotting to decrease the size of the image file; this has a negligible effect on the appearance of the figure.

* Mikulski Archive for Space Telescopes,
https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

A model for the TESS light-curve

The two sets of eclipses shown by V498 Cyg dictated the development of a bespoke model for the light-curve of the system. From this point onwards we refer to the brighter of the dEBs as binary A, which contains individual stars Aa and Ab where Aa is the primary star and has a higher surface brightness than the secondary star Ab. Similarly, the fainter dEB is referred to as binary B and the individual stars as Ba and Bb. The model of the system comprises the light contributions from the two dEBs, a third light, and a quadratic function to scale the overall light-curve to the observed magnitudes. This is expressed according to the equation

$$\ell_{\rm total}(t) \;=\; \frac{\ell_{\rm A}(t) + \alpha\ell_{\rm B}(t) + \ell_3}{1 + \alpha + \ell_3}\left[p_1 + p_2(t - t_{\rm piv}) \;+\; p_3(t - t_{\rm piv})^2\right] \qquad (1)$$

where $\ell_{\rm total}(t)$ is the total light from the system; $\ell_{\rm A}(t)$ and $\ell_{\rm B}(t)$ are the light-curves of the two dEBs, each normalized to unit flux at quadrature; and ℓ_3 is the time-independent contaminating 'third' light from any other bodies that may contribute to the light-curve, expressed as a fraction of the total light from the system. The light ratio between the two dEBs is given by α and is the ratio of the brightness of binary B to that of binary A, each taken at quadrature. Finally, the quadratic polynomial has coefficients p_1, p_2, and p_3 and is pivoted around time $t_{\rm piv}$ for numerical stability, where $t_{\rm piv}$ is a point near the centre of the data under consideration.

To calculate $\ell_{\rm A}(t)$ and $\ell_{\rm B}(t)$ we used the JKTEBOP* code[40,41]. The fitted parameters for each dEB included the sum and ratio (secondary divided by primary) of their fractional radii, the orbital inclination and period, a reference time of midpoint of the primary eclipse, and the central surface-brightness ratio of the two stars (secondary divided by primary). We adopted the quadratic limb-darkening law but fixed the coefficients to reasonable values from theoretical predictions[42]. A circular orbit was adequate for binary B but an orbital eccentricity was required for binary A. We therefore fitted for the parameters $e\cos\omega$ and $e\sin\omega$, where e is the orbital eccentricity and ω is the argument of periastron, for binary A. We also fitted for α, ℓ_3, and the polynomial coefficients.

This fitting code was named MULTEBOP and implemented in an IDL† script that called JKTEBOP to generate model light-curves and optimized the parameters of the model using the Levenberg–Marquardt method[43] as implemented in the MPFIT package[44]. Exploratory solutions were performed with the data from a single sector, binned by a factor of three, for speed. The error bars of individual datasets were scaled to yield a reduced χ^2 of $\chi^2_\nu = 1$.

Attempts to fit for the limb-darkening coefficients typically returned very similar parameters but fitted coefficients very different from the expected values and sometimes unphysical (*i.e.*, not within the interval [0,1]). The third light, however, is reliably detected. It could be caused by (yet) another stellar component in the system, imperfections in the MULTEBOP model, and/or inaccurate background subtraction in the reduction of the *TESS* data. The presence of a fifth star is the most plausible answer as the third light is approximately 10% of the total light of the system so is larger than expected for the other two explanations.

*http://www.astro.keele.ac.uk/jkt/codes/jktebop.html

†Interactive Data Language, https://www.l3harrisgeospatial.com/Software-Technology/IDL

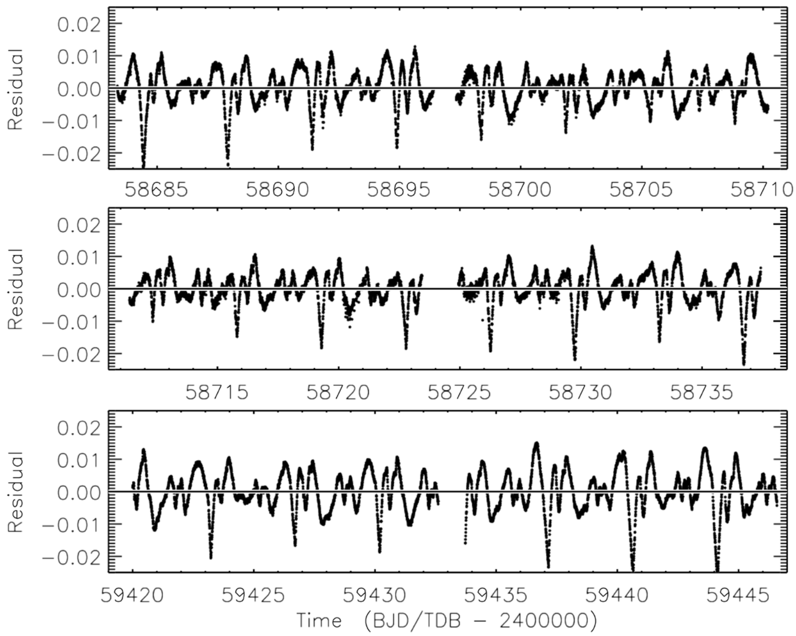

FIG. 2

Residuals of the best fits to the *TESS* SAP data in sectors 14 (top panel), 15 (middle panel), and 41 (bottom panel).

The residuals of the best fits are shown in Fig. 2, and the best fits to the individual sectors are shown in Fig. 3 for binary A and Fig. 4 for binary B. The orbital ephemerides are not reported as they will be discussed in a following section. It is clear that we are unable to obtain a good fit to these data, and this problem is most apparent in our inability to fit properly the data around the start and end of primary minimum in binary A (Fig. 3). This poor fit is the main driver for systematic variations between orbital cycles visible for binary B (Fig. 4). There are two problems here.

First, the light variation of binary A changes on the time-scale of several orbital cycles: this can be seen in the varying structure of the residuals in Fig. 2, especially during sectors 14 and 41. This effect is conceivably due to pulsations in one or both components, as they are in the region of the HR diagram where β Cephei pulsations are frequently found[45–47], or to hot spots or gas streams caused by a low level of mass transfer or stellar winds. The light-curve model is not able to produce a significant asymmetry in primary eclipse without extreme assumptions on orbital eccentricity or the reflection effect, so cannot adequately trace the true light variation in the data.

Second, the stars in *both* dEBs are significantly tidally distorted and therefore are beyond the limits of applicability of the spherical approximation implemented in JKTEBOP. The results in Table II should therefore be interpreted as indicative of the properties of the system, and not as reliable measurements of its physical properties.

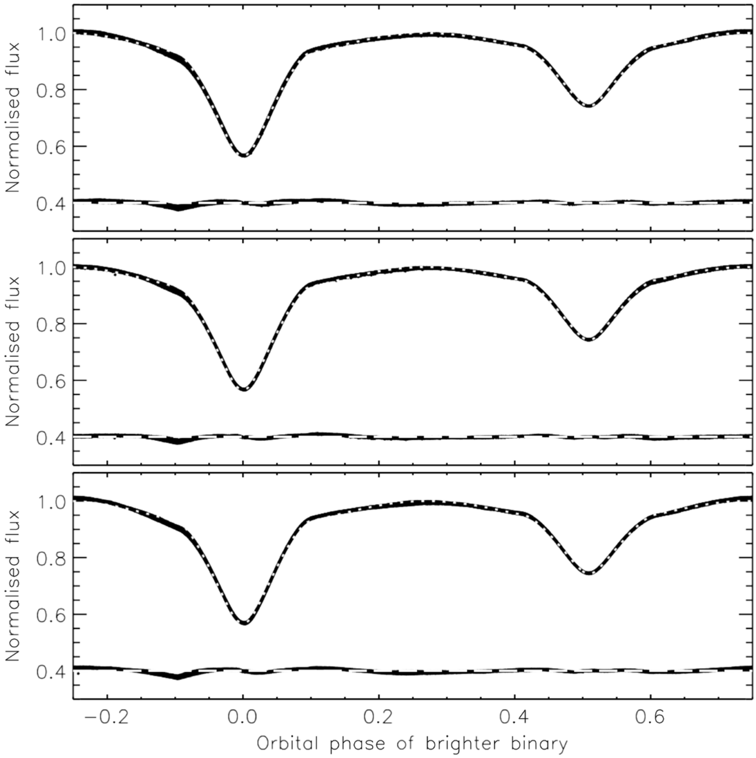

FIG. 3

Best fit to the *TESS* SAP data in sectors 14 (top panel), 15 (middle), and 41 (bottom) for binary A. In each panel the *TESS* data are shown after subtraction of the model light-curve of binary B, third light, and the quadratic function. The best fits are shown with white dotted lines superimposed on the data. The residuals are shown at the base of each panel, offset from zero.

Although we did not get a good fit to the *TESS* data, our individual fits of the three sectors returned parameter values that are highly consistent. For each parameter we took its final value to be a straight mean of the three values from the three sectors rather than fitting them all together. This is to guard against the possibility of orbital evolution and thus changing orbital periods and phases between sectors. To determine the uncertainties of the parameters we ran six separate fits, each corresponding to half of a *TESS* sector (split at the mid-sector gap for data download to Earth) and determined the standard deviation of the six values for each parameter. This process was intended to provide reliable error bars whilst avoiding the computational expense of Monte Carlo methods*. The resulting parameters and uncertainties are given in Table II. We checked for convergence problems by running multiple solutions from a range

*A single fit to one sector of *TESS* data after binning by a factor of 3 typically took approximately 6–7 minutes on the author's work laptop (a Lenovo Thinkpad L14 with Intel i5 CPU, 32GB RAM and 2TB SSD, with Kubuntu 20·04 LTS as the operating system).

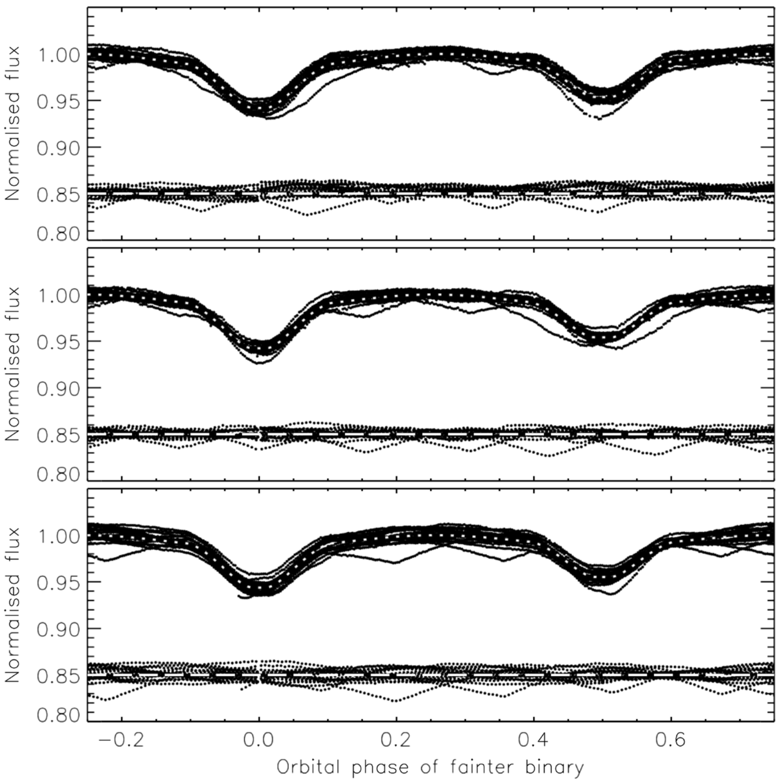

FIG. 4

Best fit to the *TESS* SAP data in sectors 14 (top panel), 15 (middle), and 41 (bottom) for binary B. In each panel the *TESS* data are shown after subtraction of the model light-curve of binary A, third light, and the quadratic function. The best fits are shown with white dotted lines superimposed on the data. The residuals are shown at the base of each panel, offset from zero.

of starting parameter values, finding that all of them converged on the same χ^2 minimum as the one corresponding to the results in Table II. We did not convert the standard deviations to standard errors as our imperfect fit to the data mean the parameter values are not reliable.

Separate fits to the light-curves of the two dEBs

We attempted to obtain a better fit to the light-curve of binary A using a code incorporating Roche geometry. We took the *TESS* light-curve from sector 14, subtracted the fitted polynomials and model for binary B, converted to orbital phase, and binned into 250 points equally spaced in phase. A fit was performed to this binned light-curve using the Wilson–Devinney (WD) code[48,49] driven by the JKTWD wrapper[50] and using the approach described in Paper 1 of this series[3].

TABLE II

Best-fitting parameters and uncertainties from the MULTEBOP fit to the three sectors of data. The parameter values are the means from fits to the three sectors individually. The uncertainties are the standard deviations (not standard errors) of the fits to six half-sectors individually.

Parameter	*Binary A*	*Binary B*
Fitted parameters:		
Orbital inclination (°)	86·96 ± 0·20	83·7 ± 1·6
Sum of the fractional radii	0·5705 ± 0·0023	0·6201 ± 0·0023
Ratio of the radii	1·2145 ± 0·0067	0·606 ± 0·032
Central surface-brightness ratio	0·5303 ± 0·0028	0·730 ± 0·064
Linear LD coefficient for primary star	0·05 (fixed)	0·08 (fixed)
Linear LD coefficient for secondary star	0·05 (fixed)	0·08 (fixed)
Quadratic LD coefficient for primary star	0·24 (fixed)	0·21 (fixed)
Quadratic LD coefficient for secondary star	0·24 (fixed)	0·21 (fixed)
$e \cos \omega$	0·01439 ± 0·00061	0·0 (fixed)
$e \sin \omega$	−0·0086 ± 0·0065	0·0 (fixed)
Light ratio between dEBs (α)	0·203 ± 0·018	
Third light	0·096 ± 0·016	
Derived parameters:		
Fractional radius of primary star	0·2576 ± 0·0013	0·3861 ± 0·0078
Fractional radius of secondary star	0·3129 ± 0·0015	0·2340 ± 0·0077
Orbital eccentricity	0·0167 ± 0·0032	0·0
Argument of periastron (°)	31 ± 15	
Light ratio	0·782 ± 0·010	0·268 ± 0·037

The same problem as before was found: the light-curve is asymmetric around the primary eclipse (most easily seen in the differing light level immediately before and after the eclipse) and this could not be matched by us using the WD code. The solution is very sensitive to the mass ratio specified, and all attempts to fit for this parameter were terminated by a failure of the least-squares minimization algorithm. As an improved fit to the light-curve was not found during this process, we do not present any fitted parameters or a plot of the best fit.

A similar approach to the light-curve of binary B conversely yielded a good fit to the data. This light-curve is 'better behaved' in the sense that it more closely conforms to the expected shape for a binary system lacking mass transfer or asymmetries in the surface brightnesses of the component stars. The parameters of the fit are more reliable than those obtained using JKTEBOP due to the use of Roche geometry rather than approximating the stars as spheres. Thanks to this relative success, the same treatment was also applied to the light-curves from sectors 15 and 41. The best fits are shown in Fig. 5, where the shapes of the total eclipses are much easier to discern than in Fig. 4. The fitted parameters are given in Table III, where the parameter values are the means from the three sectors and the error bars are the standard deviations of the quantities.

Measurement of the orbital periods

Eclipse-timing measurements of V498 Cyg can be traced back over a century, beginning with times of photographic plates when the system was noticed to be unusually faint, progressing through the eras of detailed study *via* photographic and photoelectric methods, and continuing into current times with CCD minima primarily obtained by amateur astronomers. An extensive set of eclipse

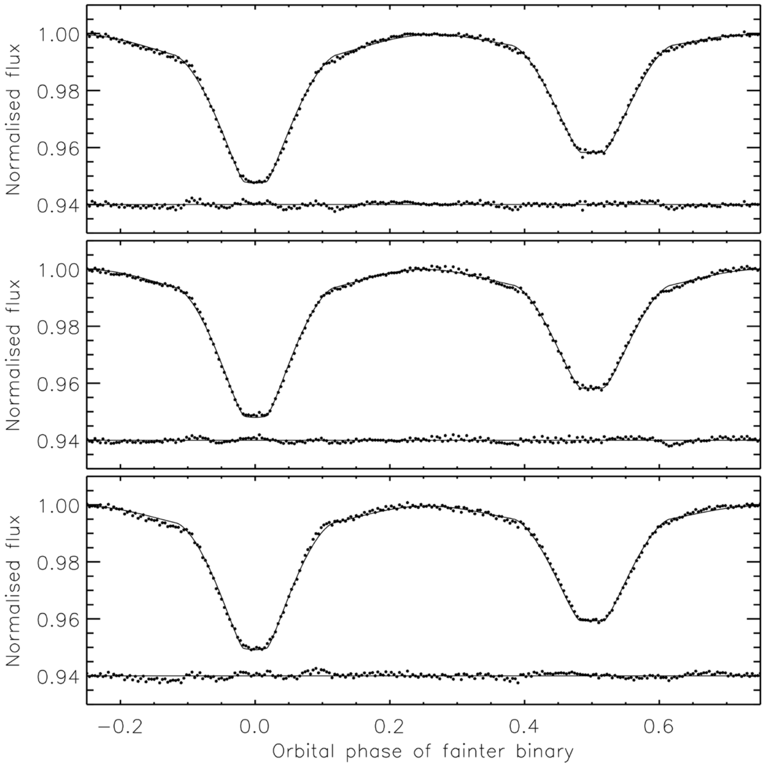

FIG. 5

Best fit to the *TESS* SAP data in sectors 14 (top panel), 15 (middle), and 41 (bottom) for binary B. The model light-curve of binary A, third light, and the quadratic function have been subtracted from the data, which has then been phase-binned using the orbital ephemeris of binary B. The best-fitting models from the WD code are shown with solid lines. The residuals are shown at the base of each panel, offset from zero.

timing measurements was kindly made available by Dr. Jerzy Kreiner (see ref. 52) to which we attempted to fit a linear ephemeris.

The results are shown in Fig. 6 and are discouraging: the scatter around the best fit is huge for the older timings (as expected), but also for the recent CCD timings. Scatters of order minutes are expected from CCD observations of systems with the brightness and eclipse depth of V498 Cyg, but instead a scatter of several hours is seen. We suspect that the presence of the eclipses from binary B has deleteriously affected many or most of the eclipse timings for binary A; other explanations are the existence of dynamical effects between the two dEBs if they are gravitationally bound, and that the eclipses of binary A last approximately 15 hr so are too long to fit into an observing night for a single telescope. For the record, the ephemeris obtained from the fit in Fig. 6 is

$$\text{Min I} = \text{BJD/TDB } 2440007{\cdot}6116 + 3{\cdot}4848627E \qquad (2)$$

TABLE III

Summary of the parameters for the WD code solution of the TESS light-curve of binary B. The quoted values and error bars are the mean and standard deviation of the values from the three sectors for each parameter. Descriptions of the control and fitting parameters of the WD code can be found in ref. 51.

Parameter	*Star Ba*		*Star Bb*
Control parameters:			
WD2004 operation mode		2	
Treatment of reflection		1	
Number of reflections		1	
Limb-darkening law		1 (linear)	
Numerical grid size(normal)		50	
Numerical grid size(coarse)		40	
Fixed parameters:			
Orbital eccentricity		0	
Rotation rates	1·0		1·0
Gravity darkening	1·0		1·0
$T_{\rm eff}$ (K)	20 000		
Bolometric limb-darkening coefficient	0·700		0·710
Linear limb-darkening coefficient	0·233		0·245
Bolometric albedos	1·0		1·0
Fitted parameters:			
Potential	3·217 ± 0·020		3·25 ± 0·11
Mass ratio		0·542 ± 0·025	
Orbital inclination (°)		88·1 ± 1·2	
Third light		0·8785 ± 0·0039	
Light contribution	1·083 ± 0·053		
$T_{\rm eff}$ (K)			16100 ± 1800
Derived parameters:			
Fractional radii	0·3860 ± 0·0033		0·2743 ± 0·0069

with a root-mean-square scatter of 5730 s (*i.e.*, 1·6 hr). This fit was performed without weighting the data because most of the eclipse timings have no quoted uncertainty and for those that do they are negligible compared to the scatter. Uncertainties in the ephemeris are not given for the same reason. The historical timings were all converted to the BJD/TDB timescale using the routines of Eastman *et al.*[53] before fitting the ephemeris.

Considering the difficulties found above, and the lack of published eclipse timings for binary B, we instead determined precise orbital periods for the two dEBs using only our fits to the three sectors of *TESS* observations. A linear ephemeris was adopted for each system and the uncertainties in the eclipse timings were scaled to yield $\chi^2_\nu = 1$ for each dEB. The timings are given in Table IV and the fits are shown in Fig. 7. The ensuing ephemerides are

$$\text{Min I} = \text{BJD/TDB } 2458723{\cdot}1091(16) + 3{\cdot}484806(16)E \qquad (3)$$

for binary A and

$$\text{Min I} = \text{BJD/TDB } 2458727{\cdot}4821(20) + 1{\cdot}438457(8)E \qquad (4)$$

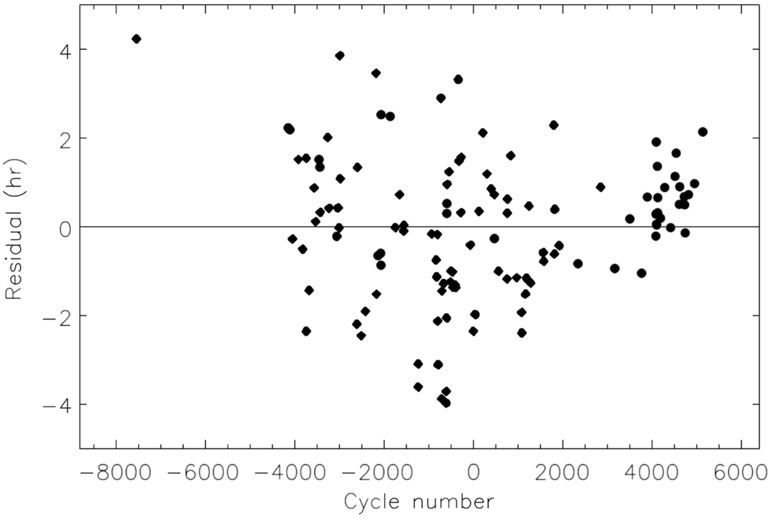

Fig. 6

Residuals of the fit of a linear ephemeris to the historical times of minimum light recorded for V498 Cyg. The dotted line divides the older timings obtained using visual, photographic, and photoelectric methods from the more recent CCD observations. Note the size of the y-axis scale.

Table IV

Timings of midpoint of primary eclipse for the two binaries for each sector, obtained using MULTEBOP. *The timings are given in BJD/TDB.*

TESS Sector	*Binary A*	*Binary B*
14	2458695·22760 ± 0·0024	2458685·7726 ± 0·0039
15	2458723·11168 ± 0·0022	2458727·4799 ± 0·0024
41	2459430·52441 ± 0·0030	2459428·0112 ± 0·0033

for binary B, where a bracketed quantity indicates the uncertainties in the final digit of the immediately preceding number. The residuals of the fits to the ephemerides of the two components are anti-correlated, suggesting the presence of mutual dynamical interactions between two gravitationally-bound binary systems. If the interpretation is correct, V498 Cyg is a particularly interesting system for future study.

Discussion and conclusions

V498 Cyg has been known to be eclipsing for over 80 yr. The *TESS* light-curve reveals a second set of eclipses which are much shallower and have a shorter orbital period (3·48 d for binary A and 1·44 d for binary B). These data

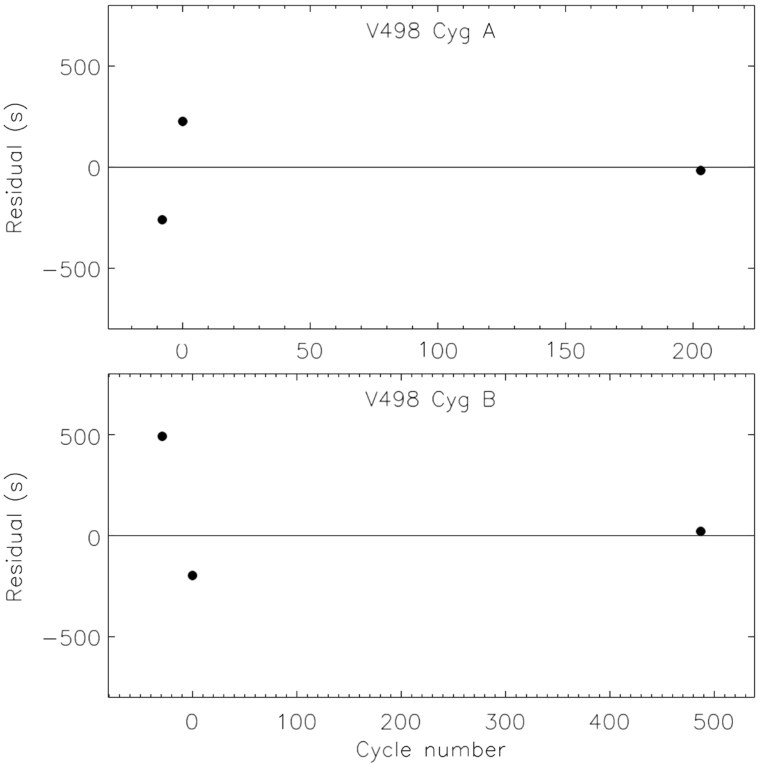

FIG. 7

Residuals of the fits of linear ephemerides to the times of minimum light measured for binary A (top) and binary B (bottom) in this work.

have been fitted using a model developed specifically for this system, MULTEBOP, which generates light-curves for the two dEBs individually using the JKTEBOP code and combines them alongside normalization polynomials and third light. This allowed all relevant parameters to be fitted together to give the overall best model.

We were, however, unable to get a good model for the system using this approach. The residuals of the fit (Fig. 2) are large, depend primarily on the orbital phase of binary A, and change during and between the time intervals covered by the data from the three *TESS* sectors. A visualization of the best fit for binary A (Fig. 3) shows a poor agreement with the shapes of the eclipses, most obviously an inability to reproduce correctly the asymmetric brightness variation at the points of first and fourth contact in the primary eclipse. There is a clear perturbation to the light-curve which may be due to pulsations, surface inhomogeneities, and/or mass-transfer processes.

The large fractional radii of all four stars prompted a separate examination of the light-curves of the two dEBs using the WD code. A good fit to binary B was obtained and some of its photometric properties were constrained to reasonable precision. Binary A was more challenging and an acceptable model of the system was not found.

We can nevertheless construct a straw-man model of the system using the constraints we have assembled, beginning with binary A. Lacy[26] found its spectral type to be B1·5 V, and the depths and widths of the spectral lines of the two components to be similar. Adopting an effective temperature of 25000 K for star Aa[54] and a zero-age main sequence isochrone for solar metallicity from the PARSEC models[55], we infer a mass of 10 $M_\odot$ and a radius of 5 $R_\odot$. Star Ab appears to be more evolved than star Aa, based on our measurement that its temperature is lower (21000 K from the surface-brightness ratio in Table II) but its radius is larger (6 $R_\odot$), so our assumption of zero age is questionable. Given the difficulties found in fitting the light-curve, we regard these properties (especially for star Ab) as unreliable. The system is expected to be young because it has a significant orbital eccentricity despite the short tidal circularization time-scale for stars of this mass and fractional radius[56], although an alternative explanation is that a small orbital eccentricity is maintained by dynamical effects if the two dEBs are gravitationally bound.

Turning to binary B, a simple scaling of its luminosity according to the light ratio between the dEBs suggests masses and radii of roughly 6·5 $M_\odot$ and 3·3 $R_\odot$, respectively, for star Ba. The mass and radius ratios from the fit with the WD code then give the equivalent properties for star Bb to be 3·5 $M_\odot$ and 2·3 $R_\odot$, which is an acceptable match to the predictions from the PARSEC models. The predicted tempertures for these masses on the ZAMS are approximately 20000 K and 14000 K, a ratio which is only mildly discrepant with the WD code fit. The estimated properties of the four stars are collected in Table V for reference.

Using Kepler's third law we infer that the semi-major axes of the relative orbits of the two dEBs are 0·13 AU and 0·05 AU. The fractional radii implied by this and the radii suggested above are all significantly lower than those actually measured. We conclude that the system has either experienced significant evolution and is beyond the zero-age main sequence, mass transfer has made the stars unrepresentative of single-star evolution, or the masses and thus orbital separations are lower than we have estimated. The straw-man model constructed above is thus unreliable. The small orbital eccentricity detected in binary A could be the result of dynamical interactions between the two dEBs. These suggestions could be refined by a more sophisticated attempt to match the measured properties of the system to theoretical models, but such an activity would have to navigate carefully the possible binary interactions suggested by the asymmetric primary eclipse in binary A. A more direct approach is possible and preferable: the system is known to show spectral lines of at least two components so determination of the spectroscopic orbits and thus masses of the two brighter stars is within reach. High-quality observations and careful analysis might also allow the spectral signatures of stars Ba and Bb to be identified and

TABLE V

Inferred properties of the four stars in the V498 Cyg system.

Property	*Binary A*		*Binary B*	
	Star Aa	*Star Ab*	*Star Ba*	*Star Bb*
Mass ($M_\odot$)	10	11	6·5	3·5
Radius ($R_\odot$)	5	6	3·3	2·3
Temperature (K)	25000	21000	20000	14000
log g (log c.g.s)	4·0	3·9	4·2	4·3

measured. Finally, one more sector of observations with *TESS* is scheduled in 2022 August. It will be interesting to see whether this light-curve exhibits the same eclipse shapes as those used in the current study, and whether the new eclipse timings reveal clearer evidence of dynamical interactions between the two components of the doubly-eclipsing quadruple star system V498 Cygni.

Acknowledgements

We thank Dr. Jerzy Kreiner and Dr. Tamás Borkovits for helpful discussions during the analysis presented above, and the anonymous referee for a very helpful and exceptionally fast report. This paper includes data collected by the *TESS* mission. Funding for the *TESS* mission is provided by the NASA's Science Mission Directorate. The following resources were used in the course of this work: the NASA Astrophysics Data System; the *Simbad* database operated at CDS, Strasbourg, France; and the arχiv scientific paper preprint service operated by Cornell University.

References

(1) J. Andersen, J. V. Clausen & B. Nordström, *ApJ*, **363**, L33, 1990.
(2) G. Torres, J. Andersen & A. Giménez, *A&ARv*, **18**, 67, 2010.
(3) J. Southworth, *The Observatory*, **140**, 247, 2020.
(4) G. Duchêne & A. Kraus, *ARA&A*, **51**, 269, 2013.
(5) H. Sana *et al.*, *ApJS*, **215**, 15, 2014.
(6) M. R. Bate, *MNRAS*, **392**, 590, 2009.
(7) M. R. Bate, *MNRAS*, **484**, 2341, 2019.
(8) M. Moe, K. M. Kratter & C. Badenes, *ApJ*, **875**, 61, 2019.
(9) A. B. Justesen & S. Albrecht, *ApJ*, **912**, 123, 2021.
(10) C. U. Lee *et al.*, *MNRAS*, **389**, 1630, 2008.
(11) P. Cagaš & O. Pejcha, *A&A*, **544**, L3, 2012.
(12) G. Torres *et al.*, *ApJ*, **846**, 115, 2017.
(13) H. Lehmann *et al.*, *A&A*, **541**, A105, 2012.
(14) K. G. Hełmíniak *et al.*, *A&A*, **602**, A30, 2017.
(15) T. Borkovits *et al.*, *MNRAS*, **478**, 5135, 2018.
(16) P. Rowden *et al.*, *AJ*, **160**, 76, 2020.
(17) T. Borkovits *et al.*, *MNRAS*, **503**, 3759, 2021.
(18) V. B. Kostov *et al.*, *ApJ*, **917**, 93, 2021.
(19) I. M. Volkov, A. S. Kravtsova & D. Chochol, *arXiv:*2107*.09116*, 2021.
(20) J. Southworth, *Universe*, **7**, 369, 2021.
(21) A. J. Cannon & E. C. Pickering, *Annals of Harvard College Observatory*, **100**, 1, 1936.
(22) E. Høg *et al.*, *A&A*, **355**, L27, 2000.
(23) Gaia Collaboration *et al.*, *A&A*, **649**, A1, 2021.
(24) K. G. Stassun *et al.*, *AJ*, **158**, 138, 2019.
(25) R. M. Cutri *et al.*, *2MASS All Sky Catalogue of Point Sources* (The IRSA 2MASS All-Sky Point Source Catalogue, NASA/IPAC Infrared Science Archive, Caltech, US), 2003.
(26) C. H. Lacy, *IBVS*, **3448**, 1, 1990.
(27) W. A. Hiltner, *ApJS*, **2**, 389, 1956.
(28) C. Hoffmeister, *AN*, **259**, 37, 1936.
(29) H.-U. Sandig, *AN*, **276**, 173, 1948.
(30) Y. E. Einasto, *Peremen. Zvezdy*, **8**, 71, 1941.
(31) G. Romano, *Memorie della Societa Astronomica Italiana*, **40**, 375, 1969.
(32) N. L. Magalashvili & I. I. Kumsishvili, *Abastumanskaia Astrofizicheskaia Observatoriia Byulleten*, **49**, 3, 1978.
(33) P. Mayer *et al.*, *BAICz*, **42**, 225, 1991.
(34) A. B. Smith & D. B. Caton, *IBVS*, **5745**, 1, 2007.
(35) J. Hubscher & P. B. Lehmann, *IBVS*, **6149**, 1, 2015.
(36) M. M. Zakirov & M. U. Eshankulova, *Kinematics and Physics of Celestial Bodies*, **24**, 77, 2008.
(37) N. L. Eisner *et al.*, *MNRAS*, **501**, 4669, 2021.
(38) G. R. Ricker *et al.*, *Journal of Astronomical Telescopes, Instruments, and Systems*, **1**, 014003, 2015.
(39) J. M. Jenkins *et al.*, in *Proc. SPIE*, 2016, *Society of Photo-Optical Instrumentation Engineers* (*SPIE*) *Conference Series*, vol. 9913, p. 99133E.

(40) J. Southworth, P. F. L. Maxted & B. Smalley, *MNRAS*, **351**, 1277, 2004.
(41) J. Southworth, *A&A*, **557**, A119, 2013.
(42) A. Claret, *A&A*, **618**, A20, 2018.
(43) D. W. Markquardt, *J. Soc. Ind. Appl. Math.*, **11**, 431, 1963.
(44) C. B. Markwardt, *Astronomical Society of the Pacific Conference Series*, **411**, 251, 2009.
(45) P. Walczak *et al.*, *A&A*, **580**, L9, 2015.
(46) J. Southworth *et al.*, *MNRAS*, **497**, L19, 2020.
(47) J. Southworth, D. M. Bowman & K. Pavlovski, *MNRAS*, **501**, L65, 2021.
(48) R. E. Wilson & E. J. Devinney, *ApJ*, **166**, 605, 1971.
(49) R. E. Wilson, *ApJ*, **234**, 1054, 1979.
(50) J. Southworth *et al.*, *MNRAS*, **414**, 2413, 2011.
(51) R. E. Wilson & W. Van Hamme, *Computing Binary Star Observables* (Wilson–Devinney program user guide), available at ftp://ftp.astro.ufl.edu/pub/wilson, 2004.
(52) J. M. Kreiner, C.-H. Kim & I.-S. Nha, *An atlas of O-C diagrams of eclipsing binary stars*, 2001.
(53) J. Eastman, R. Siverd & B. S. Gaudi, *PASP*, **122**, 935, 2010.
(54) M. J. Pecaut & E. E. Mamajek, *ApJS*, **208**, 9, 2013.
(55) A. Bressan *et al.*, *MNRAS*, **427**, 127, 2012.
(56) J. Zahn, *A&A*, **57**, 383, 1977.

REVIEWS

Solar Energetic Particles: A Modern Primer on Understanding Sources, Acceleration and Propagation, 2nd Edition, by Donald V. Reames (Springer), 2021. Pp. 225, 23·5 × 15·5 cm. Price £34·99/$49·99 (paperback; ISBN 978 3 030 66401 5).

In this recent addition to Springer's *Lecture Notes in Physics*, Donald V. Reames presents a clear contemporary account of observational and theoretical studies of the principal families of solar energetic particles (SEPs) with an introduction to measurements of SEPs. SEPs are high-energy particles from the Sun with durations lasting hours (impulsive events) to days (gradual events) with energies from keV to GeV. SEPs from impulsive events are accelerated near solar flares or jets and SEPs from gradual events are accelerated at several solar radii above the solar surface by shocks linked to coronal mass ejections. These sites of SEP acceleration above the solar surface are largely inaccessible by photons but may be investigated through relative abundances of elements (H to Pb) and isotopes of abundant elements which reflect the physical processes responsible for the acceleration and transport of SEPs. A delightful sense that this lively presentation is drawn from Reames' decades of experimental investigations of SEPs pervades the book.

SEPs, in combination with the solar wind, represent the solar mass-loss rate. The solar wind consists of fast and slow components, as discussed briefly by Reames. The fast solar wind originates in coronal holes. The origin of the slow wind appears to have resisted determination. Reames notes that "SEPs and the solar wind are fundamentally different samples of coronal material". The composition of SEPs and solar wind differ in interesting ways from the composition of the solar photosphere. Reames provides a clear description of such differences and their links to the physics of particle acceleration and transport, especially for SEPs. Given that the Sun's mass-loss rate is so very low, a stellar astronomer might be forgiven for ignoring descriptions of the composition of SEP events (and the solar wind). My experience tells me that it is not unlikely that, as spectroscopic determinations of stellar abundances expand in scope and precision, a well-read, alert stellar astronomer may find an occasion to revisit this book for insights.

A very extraordinary isotope ratio observed in some SEP events is the ^{4}He/^{3}He ratio which can approach unity, yet ^{4}He is about 2000 times more abundant than ^{3}He in the solar wind and the local interstellar medium. Surely, curiosity is aroused by this 2000-fold anomaly. Unusual B-type stars with a ^{4}He/^{3}He ratio near unity are known, beginning with Sargent & Jugaku's 1961 classic paper on 3 Cen A, but the origins of this peculiar isotopic ratio in 3 Cen A and SEP events are surely different. Yet, the physics behind SEP events may account for other astronomical anomalies.

Elemental and isotopic abundance measurements of particles in SEP events and the solar wind offer opportunities to fill gaps set by limitations of spectroscopic analysis of the solar photospheric spectrum. In the latest compilation of the solar composition, the solar wind is the source of the Ne, Ar, and Kr abundances. Elemental abundances in gradual SEP events and solar-wind samples differ from photospheric abundances by a factor dependent on an element's first ionization potential (FIP). The FIP effect is discussed by Reames who introduces Laming's theory based on 'the ponderomotive force of Alfvén waves' below the corona's base which preferentially feeds low-FIP ions (*e.g.*, Na, Ca, Mg, Fe) into the corona ahead of high-FIP ions (*e.g.*, O, Ne, Ar). Again, the FIP effect should attract attention beyond the solar-physics community, especially observers of stars displaying high levels of stellar activity.

In summary, this excellent primer by Reames is a thorough account of SEP events with parallel discussions of the solar wind. It deserves to be read by stellar astronomers. Since it is available by 'Open Access', the normal complaint about a book's cost is here inapplicable. — David L. Lambert.

Magnetic Fields in O, B, and A stars, by Swetlana Hubrig & Markus Schöller (IoP Publishing), 2021. Pp. 190, 26 × 18·5 cm. Price £120/$190 (hardbound; ISBN 978 0 7503 2390 1).

The 'AAS–IoP Astronomy ebooks' series, to which this volume is a recent addition, is rapidly becoming established as a major source of specialized monographs, with more than 30 books already available at the time of writing, and a similar number in preparation (according to the series' web site). Many (though not all) of the titles are so specialized that in days past one may have associated them with review papers, not books. The volume under review is no exception.

Although OBA stars share the common characteristic of having predominantly radiative envelopes — so that observable magnetic fields are likely to be fossil remnants, not dynamo driven — in practice only the BA dwarfs have a long-established record of investigations, going back to Babcock's first measurement of a stellar field (other than the Sun's) in 1946. Our understanding of this subgroup, built on the foundation of Stibbs' simple offset-dipole model, is correspondingly mature. In contrast, the first detection of an O-star field didn't occur until this century, following the development of a new generation of dedicated high-resolution spectropolarimeters with much improved sensitivity. The physics of the interaction of stellar-wind outflows with the magnetic fields is under continuing active investigation.

With such a narrowly focussed topic, the authors are able to review the literature (to which they are substantial contributors) rather thoroughly, incorporating a lot of detail on individual objects. I was left wondering who would want to work through such an exhaustive treatise; the stated aim is "to educate scientists working on [early-type] stars, who are not yet expert in magnetic field studies". Well, okay, though I'd have thought that active researchers will already be familiar with the material, while those outside the field may find it hard to see the wood for the trees. Perhaps the answer is new postgraduate students about to undertake a relevant project, though that can't be more than a handful of people each year. In any case, this is really a book for the specialist, although a couple of introductory chapters provide a more general introduction to the principles and practice of magnetic-field measurement that may be of wider interest.

As with other books in the series, the hardbound edition is nicely produced, with colour illustrations used throughout, although as usual there's no index. The cover price may act as a deterrent to personal purchasers, but, of course, the series is promoted principally in electronic formats, and there's a reasonable chance that professional scientists will find that they have 'free' (at the point of use) access through their institutional library. In that case, they can also avail themselves of the IoP 'myPrint' service, to obtain a personal copy through print-on-demand; there are some limitations (notably black-and-white content), but the pricing is quite reasonable. — Ian D. Howarth.

General Relativity: The Essentials, by Carlo Rovelli (Cambridge University Press), 2021. Pp. 180, 23 × 15·5 cm. Price £14·99/$19·99 (paperback; ISBN 978 1 00 901369 7).

In a recent review[1] in these pages, I wrote "There is no shortage of books on GR [General Relativity], and none of *good* books on GR, but levels and approaches differ." One main difference between various GR books is whether differential geometry and the Einstein equation are introduced first, before applications, or *vice versa*, with mathematics being introduced as needed. I generally prefer the second approach, but I think that the first approach is better for a book such as this since, at just 180 pages, including introductory chapters on physics and philosophy and a final one on quantum gravity, it is much shorter than a typical GR textbook. Although it is a textbook, as the title says it concentrates on the essential aspects of GR. The usual suspects — curvature, gravitational waves, cosmology, some solutions for special cases, black holes — are all here, but also more discussion of concepts than one finds even in some much longer texts. From other books by Rovelli (one reviewed[2] in this *Magazine*) I'm familiar with his ability to condense concepts to short but meaningful statements; in this book, for example, he notes that Galilean relativity expresses the idea that the concept of being in the same place at different times is ill-defined (relative to what?), while Special Relativity expresses the idea that the concept of happening at the same time in different places is equally ill-defined.

While it might be difficult to learn GR in detail (even just regarding the topics discussed) from this book alone, it is possible to learn the basic concepts, and at a deeper level than the typical popular-science presentation. As such, the book serves as a good introduction for those who afterwards want to move on to learning GR in detail using the standard textbooks; it is much easier (at least for me) to follow mathematical derivations and so on if the concepts are already clear. But even for those who know it all, it is useful to have a summary of the main concepts and results, especially as a bridge to other disciplines. Rovelli is probably best known as a researcher on Loop Quantum Gravity (LQG), probably the main rival (there are others[3]) to string theory as (a path to) a theory of quantum gravity. That is reflected in the final chapter, which is a basic introduction to quantum gravity, concentrating on LQG. (I would like to see a book on that topic of about the same length and at about the same level as the book reviewed here; there are technical monographs and popular-level expositions, but nothing in-between.) His own take on things also comes through in the emphasis on the underlying philosophy and concepts. He states clearly that the Universe is accelerating due to the cosmological constant and "not any mysterious 'quantum vacuum energy' or 'dark energy' ". Certainly there is no evidence (and people have looked for it) that dark energy is anything more than the cosmological constant. His conviction (which I tend to share) is related to his claim that the infamous cosmological-constant problem is, in fact, not a problem at all[4], somewhat similar to my quest to convince the community that the same is true of the flatness problem[5].

The twelve chapters are divided into three parts: 'Bases', 'The Theory', and 'Applications'. The main chapters are followed by three-and-one-half pages of suggestions for further reading, grouped by topic, and a two-and-one-half-page small-print index. There are a few black-and-white figures throughout the book. The number of typos and so on is about average for the books I review, but in the preface Rovelli invites the reader to point them out to him.

It is nice to see front-line researchers, at least those who do it well, taking the time to write for a wider readership than their immediate colleagues; Rovelli is one of the best current examples. The book is interesting, well written, and fills an otherwise vacant niche. Recommended. — PHILLIP HELBIG.

References

(1) P. Helbig, *The Observatory*, **141**, 303, 2021.
(2) P. Helbig, *The Observatory*, **136**, 155, 2016.
(3) P. Helbig, *The Observatory*, **142**, in press, 2022.
(4) E. Bianchi & C. Rovelli, *Nature*, **466**, 321, 2010 (longer version at arXiv:1002.3966).
(5) P. Helbig, *Eur. Ph. J. H*, **46**, 10, 2021.

Introduction to the Standard Model and Beyond: Quantum Field Theory, Symmetries and Phenomenology, by Stuart Raby (Cambridge University Press), 2021. Pp. 619, 25 × 18 cm. Price £59·99/$79·99 (hardbound; ISBN 978 1 108 49419 9).

I received this book at a time when covid-related restrictions meant I hadn't seen many of my colleagues in months — reading through Stuart Raby's book was a nice reminder of the importance and elegance of the Standard Model and gave an excellent insight into the many exciting areas of research beyond it that are still active today.

The book starts at an introductory level but quickly progresses, following an historical approach to cover the foundations of the Standard Model. Each chapter is short and focussed so information is easy to find and refer back to if needed. In particular, this book would be worth picking up for the chapter on spin alone — in nine pages the author gives perhaps the clearest treatment I have seen.

The rest of the book covers the Standard Model itself, as well as extensions such as neutrino masses, Grand Unification, and Supersymmetry. The mathematics has to be carefully followed step-by-step if the reader wishes to follow each chapter, but frequent diagrams and puzzles break up the difficult maths.

Notably, there is an entire chapter on the *LHC* — this is a welcome addition and helps to ground an abstract and difficult subject in reality. In a few short pages the reader gets a feel for the challenge of detecting new physics in a collider, as well as the scale of the experiments and collaborations that make them possible. It does however focus exclusively on the general-purpose detectors; as a PhD candidate with the *LHC* 'beauty experiment', I would have liked to see some treatment of the smaller experiments!

Several figures in the text are reproduced in a colour-plate section, which are nice to look at and much more readable than their monochrome counterparts. The CKM angle and neutrino-mass-constraint diagrams especially benefit from being shown in colour.

The book is clearly aimed at graduate students, but would also be suitable as a companion for an advanced undergraduate course. Worked examples are included throughout the book, with additional homework problems at the end of the early chapters. It is largely a stand-alone text, but students may benefit from something more foundational if this is their first course in Quantum Field Theory. Suggestions for independent research projects are included at the end of the book, which would particularly benefit late-undergraduate or early-postgraduate students. The short and digestible chapters make this book a good reference text, to use as a companion to a particle-physics lecture course or otherwise. — Richard Lane.

The Astronomer's Chair: A Visual and Cultural History, by Omar W. Nasim (MIT Press), 2021. Pp. 295, 23·5 × 18·5 cm. Price $60 (about£43) (softbound; ISBN 978 0 262 04553 7).

In these days of remote observation, the observing chair is whatever happens to be available to seat the user comfortably in front of the computer screen, because fewer and fewer observers are actually outdoors, looking directly through the eyepiece. I happen to be one of those, however, so I was particularly interested in looking at this new arrival from MIT Press. Omar Nasim is an historian of science, but he is also at the Institute of Philosophy at the University of Regensburg, so that this was never going to be a straightforward history of chairs, couches, and observing platforms.

The point of the observing chair is simple: it is to place the observer at the eyepiece in such a way that he feels totally relaxed and can concentrate fully on what he is seeing through the eyepiece. It is certainly true that valuable observing time can be lost, moving chairs constantly to re-position oneself as the telescope continues its inexorable movement towards the west, which has produced a whole series of ingenious solutions to try and ameliorate this situation. As telescopes became bigger, with a consequently larger arc of movement of the eyepiece, the problem of placing the observer at the eyepiece was firstly solved by arranging that the observing floor was movable, and latterly by seating the observer on the telescope so that he rode around with it.

Those interested in the observing chair and its changing form throughout recent history will need to be very selective when reading the text. There are five main chapters, although the author admits that the discussion of observing chairs does not start until Chapter 3, and that "*The Astronomer's Chair* is first and foremost a general cultural history that is concerned with representations, particularly visual ones (and sometimes textual ones as well) of chairs in a science like astronomy".

For observers, Chapters 3 and 5 are the meat of the book. Chapter 4 is called 'Cross-legged Astronomy' and discusses the early Middle-Eastern astronomers and teachers, and the attitude of westerners who visited the lands in question.

The book is well-written, well-researched, and wide ranging, but a little too heavy on the philosophical aspects for this reviewer. — R. W. ARGYLE.

A Guide to Monte Carlo Simulations in Statistical Physics, 5th Edition, by David P. Landau & Kurt Binder (Cambridge University Press), 2021. Pp. 564, 25 × 17·5 cm. Price $69·99/$89·99 (hardbound; ISBN 978 1 108 49014 6).

Recent years have seen a substantial pulse of astronomical interest in Monte Carlo methods, especially through the statistical apparatus of Markov-chain exploration of complicated model parameter spaces. To this can be added the particle-based N-body simulations that are common in cosmology in particular. With this background in mind, I was interested to see if insights into Monte Carlo methods from other areas of physics might have something usefully novel to offer to astronomy. In the event I didn't spot so much that seemed likely to be immediately applicable. The focus here is strongly on specific topics of interest in condensed matter: phase transitions in general, and in particular problems based on a lattice — pre-eminently the Ising model. Later sections discuss more fully quantum-mechanical issues, leading up to lattice gauge theory. At the very end, there is a digest of applications of Monte Carlo methods "at the periphery of physics". Astrophysics gets a whole one page to itself, devoted entirely to radiative transfer. Apart from the specific choice of topics, another reason this book is probably less useful to the non-specialist is that it is not very pedagogical, and discussion quickly degenerates to analysis of results from the research literature in condensed matter. It would probably be possible to write a text on this material that could be read with profit (or at least interest) by non-specialists, but this is not that book. — JOHN PEACOCK.

Annual Review of Earth and Planetary Sciences, Vol. 49, 2021, edited by R. Jeanloz & K. H. Freeman (Annual Reviews), 2021. Pp. 728, 24 × 19·5 cm. Price from $524 (print and on-line for institutions; about £387), $118 (print and on-line for individuals; about £86) (hardbound; ISBN 978 0 8243 2049 2).

Back in the UK at last, no end in sight of Covid-19, and along comes Volume 49 of *Annual Review* to turn our thoughts to other things. The usual varied menu of diverse topics is offered, covering a wide range of terrestrial and Solar System subjects. Geodynamics offerings include chapters on collision tectonics (Iran) and the involvement of continental lithosphere keels in the motion of plates — a little complication that is all too often ignored. These chapters are underpinned by several on various flavours of geochemistry and links to the cycling of diverse chemical species in the solid Earth, atmosphere, and hydrosphere. Chapters cover the Laurentian Great Lakes and the cycling of material in the mantle. There is still a certain amount of assumption that material travels through the entire mantle, down to the core–mantle boundary and back to the surface, and one wonders how the picture would change if this happened not to be so. Volatiles are amply covered this year, both as regards planetary evolution (Mars) and Earth's own inventory.

Climate is dealt with in a somewhat unusual (for a geological book) review of risk management. More traditionally, the Holocene temperature history and its impact on the Greenland icecap is discussed, along with a useful update of what is known about the CO_2 content of Earth's atmosphere during the Cenozoic. Seismology is represented by chapters both traditional and exotic. In the latter category is a chapter on the emerging technology of fibre-optic seismology — the use of fibre-optic cables as strain sensors. This is definitely a subject worth keeping an eye on because if you look differently you see differently. An important chapter reviews submarine landslides, which can be catastrophically tsunamigenic.

Igneous petrology is represented by chapters on melt samples large and small, ranging from entire volcanic arcs to melt inclusions in single crystals. The bottom line seems to be that the further back you stand the simpler things look. So if you are looking for trouble, get close up.

I always like to set special time aside to peek at the end of a book, to see what is desperately trying to hide. This year, *Annual Review* finishes with an update on what might arguably be claimed to be the most amazing and exotic process known in the Solar System — the plate tectonics that is seen uniquely on our own planet. Christopher Scotese walks us through the very latest of his ever-improving history in pictures of the evolution of the surface of Earth. That chapter, at the very end of the book, surely makes an excellent and appropriate read for the very beginning of geology courses anywhere.

As usual the volume is enhanced by beautiful illustrations and printed and bound to an excellent quality. Definitely recommended while we sit out what hopefully is the tail end of our Covid tribulations. — Gillian Foulger.

The Greatest Adventure: A History of Human Space Exploration, by Colin Burgess (Reaktion), 2021. Pp. 338, 23·5 × 15·5 cm. Price £25 (hardbound; ISBN 978 1 78914 460 4).

In 2021 April the world celebrated the sixtieth anniversary of the first human spaceflight by Soviet cosmonaut Yuri Gagarin. Since then, some 550 people have followed in Gagarin's wake and 12 have even walked on the Moon.

This book, part of a series about astronomy and space, retells the largely familiar story of the triumphs and tragedies that have accompanied humanity's efforts to leave planet Earth and learn how to work and survive in the hostile environment of outer space. The guide to this adventure is Colin Burgess, a long-term observer of human spaceflight and the author of many books on space exploration. Burgess gives a detailed account of the space age, starting with the first pioneers of Vostok and Mercury, progressing to the Moon race — which turned out to be very one-sided — and the Apollo landings, before describing the chequered history of the Soviet space stations and US *Skylab*.

The decades dominated by the Space Shuttle and the *International Space Station* also receive their merited attention. The final chapters give a surprisingly brief overview of recent developments, such as the ambitious Chinese human spaceflight programme, space tourism, and NASA's efforts to return to the Moon with its Artemis programme.

Well illustrated with black-and-white photos, this is a very readable account of the first six decades of humanity's efforts to access and utilize near-Earth space, and highly recommended for anyone who is unfamiliar with the remarkable international endeavours that have opened up the final frontier. For anyone who wants to delve further, a useful list of references is provided. — Peter Bond.

Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space, by Sandra Häuplik-Meusburger & Sheryl Bishop (Springer), 2021. Pp. 250, 24 × 16 cm. Price £109·99/$159·99 (hardbound; ISBN 978 3 030 69739 6).

Space is an extreme environment. That rather trivial observation, however, leads to a whole complexity of issues when we come to launch the human organism into it. In this wide-ranging book that is both thorough and infused with decades of combined experience from the authors, we get a full treatment of how humans will live beyond Earth. For me, as a microbiologist, the book represents a new context of the pervasive term 'habitability'. Instead of applied to environments where we might look for microbial life, it is here applied to humans.

The book provides an excellent historical perspective on knowledge gained about human physiology, psychology, and confinement in locations on Earth such as Antarctica and previous space stations. But rather than merely give us history, all this prior knowledge is well fused together and woven throughout discussion of what the lessons are, and how we might apply them. For anyone who wants to know about how we can successfully build spacecraft and settlements beyond Earth, they will find that they learn from the past and are filled with a rich discussion of criteria and suggestions for how to do this in the future.

The authors do a thorough job of comparing extreme environments. There are enough stations in various extreme locations from the Antarctic and Arctic and deserts in between to ask what is common about these environments and what general lessons we can extract. In a fascinating chapter that takes us essentially on a guided tour of existing facilities, we get to think about these questions and see how these stations are constructed and designed in their interiors. There are also many diagrams and station layouts presented in this book, which augment the discussion well. You can actually see the designs for yourself. If you are thinking about any space-habitat design, you will find this very useful, whether that's a serious engineering exercise or as an assignment as part of an outreach activity.

Beyond the functional requirements, architecture and design is fundamental to making spaces habitable. Spacecraft builders and designers are often focussed on the cold needs of survival. Yet, of course, the environments we live in influence our psychology and well-being. The authors discuss the architectural design of enclosed spaces in some detail across several of the chapters, again drawing on the lessons learned from the growing number of analogue experiences.

The title of their last chapter could well have been the title of the book: 'How to convert a tin can into a home'. One could say that this essentially summarizes the entire problem of the human existence in space. Beyond life support, how do we turn space into a place where people do not merely survive, but feel like they can live there. The authors examine factors such as crowdedness, the need for green space, the role of food, what possessions you need, and many other factors that collectively define how we feel in confined spaces and how we might turn them into humane spaces. This is backed up by survey and subject-study data.

This book is well written and easy to read. Yet, despite the ease of reading, it's also full of useful information that one can also consider it a resource. I don't write that much about the details of habitat space, but I've already cited it in a work about freedoms beyond Earth. I suspect many others will find it intersects

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with other fields and questions related to the human presence in space. From that point of view, it should sit on your bookshelf. All in all, a very valuable and well executed work by leaders in this field. — Charles Cockell.

Other Books Received

Solar Polarization 8. In Honor of Egidio Landi Degl'Innocenti (ASP Conference Series, Vol. 526), edited by L. Belluzzi *et al.* (Astronomical Society of the Pacific), 2019. Pp. 376, 23·5 × 15·5 cm. Price $88 (about £69) (hardbound; ISBN 978 1 58381 939 5).

The proceedings of a workshop held in Florence, Italy, in 2016 September.

Astronomical Data Analysis Software and Systems XXIX (ASP Conference Series, Vol. 527), edited by Roberto F. Pizzo *et al.* (Astronomical Society of the Pacific), 2020. Pp. 817, 23·5 × 15·5 cm. Price $88 (about £69) (hardbound; ISBN 978 1 58381 941 8).

Proceedings of a conference held in Groningen, the Netherlands, in 2019 October.

Galactic Center Workshop 2019: New Horizons in Galactic Center Astronomy and Beyond (ASP Conference Series, Vol. 528), edited by Masato Tsuboi & Tomoharu Oka (Astronomical Society of the Pacific), 2020. Pp. 461, 23·5 × 15·5 cm. Price $88 (about £69) (hardbound; ISBN 978 1 58381 943 2).

Proceedings of a workshop held in Yokohama, Japan, in 2019 October.

THESIS ABSTRACTS

Cosmological Distances: Calculation of Distances in Cosmological Models with Small-Scale Inhomogeneities and Their Use in Observational Cosmology

By Phillip Helbig

In cosmology, one often assumes that the Universe is homogeneous and isotropic. While originally a simplifying assumption, today there is observational evidence that this is a good approximation in our Universe on scales above a few hundred megaparsecs. This approximation is often used when calculating various distances as a function of redshift, even though the scales probed by a beam of light are much smaller than the scale of homogeneity. Since our Universe is obviously not homogeneous and isotropic on small scales, it is at least conceivable that this could affect distance calculation.

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Two models have been proposed in order to take such small-scale inhomogeneities into account in a relatively simple way. One, due to Zel'dovich, involves a two-component universe where one component is smoothly distributed and the other in clumps, with the assumption that, when calculating distance from redshift, light propagates far from all clumps. Under those assumptions, one can derive a second-order differential equation for the distance. This is a simple *ansatz* but it is not obvious how valid it is. Another approach, originally due to Einstein and Straus but developed with regard to cosmological-distance calculation by Kantowski, involves removing material from a spherical region of an otherwise smooth universe and redistributing it inside this sphere (*e.g.*, as a point mass at the centre, as a shell at the boundary, or in a more complicated manner). This *ansatz* is more difficult for calculations, but is an exact solution of the Einstein equations, so there is no question about its validity (how realistic such a mass distribution is as a model of our Universe is a separate question). Long after both had been investigated in detail, Fleury showed that they are equivalent at a well-controlled level of approximation.

After a review of the history of those two approaches, I present my own work in this area: an efficient numerical implementation for the solution of the most general form of the differential equation (*i.e.*, arbitrary values of λ_0, Ω_0, and the homogeneity parameter η, the last indicating the fraction of matter distributed smoothly), a discussion of the uncertainty in distance calculation due to uncertainty in the value of η, the effect of η on the calculation of H_0 from gravitational-lens time delays, the effect of η on the separation between images in a gravitational-lens system, and the effect of η on the determination of λ_0, and Ω_0 from the m–z relation for type Ia supernovae — including evidence that observations indicate that, in our Universe, the standard distance is a good approximation, even though small-scale inhomogeneities can be appreciable, probably because the Zel'dovich model does not accurately describe our Universe. — *University of Liège*; *defended 2021 October 19*.

A paper copy of the thesis can be requested from helbig@astro.multivax.de or by writing to the author at Thomas-Mann-Str. 9, D-63477 Maintal, Germany; a PDF version is available at https://orbi.uliege.be/handle/2268/264058

Outflows and Dust in Quasars

By Matthew J. Temple

Supermassive black holes (SMBHs) at the centres of galaxies are known to accrete actively, forming so-called 'active galactic nuclei' (AGN) or 'quasars'. These AGN are believed to feed energy back into their host galaxies, regulating star formation and the growth of the SMBH itself. This thesis investigates the outflow properties in quasars at $1 < z < 3$, corresponding to the peak epoch of galaxy formation and SMBH growth.

First, I make use of recent improvements to atomic-energy-level data and photoionization models to constrain the properties of the Fe III-emitting material in quasars[1]. I show that this material must be dense and micro-turbulent to explain the observed strength of emission, and thus arise from the inner parts of the broad-line region. The strength of this emission is shown to correlate with the outflow properties.

Second, I develop an SED model capable of reproducing the median observed photometric colours in the SDSS quasar population[2]. This model is then used to investigate the properties of the emission from the hottest, sublimation-temperature dust components in the near-infrared spectra of quasars[3]. This dust is believed to be located at the inner edge of the toroidal obscuring structure. The strength of hot-dust emission is found to correlate with the quasar outflow properties, providing evidence of a link between the broad-line region and the dusty structures surrounding the inner regions of the AGN.

Finally, I quantify the outflow properties in a sample of heavily dust-reddened quasars[4]. When matched in redshift and luminosity, there is no significant difference between the outflow kinematics of reddened and unobscured quasars. Assuming a paradigm in which dust-reddened quasars arise from major galaxy mergers, quasar-driven outflows must therefore persist after the obscuring dust is cleared from the line of sight. — *University of Cambridge; accepted 2021 January*.

References

(1) M. J. Temple *et al.*, *MNRAS*, **496**, 2565, 2020.
(2) M. J. Temple *et al.*, *MNRAS*, **508**, 737, 2021.
(3) M. J. Temple *et al.*, *MNRAS*, **501**, 3061, 2021.
(4) M. J. Temple *et al.*, *MNRAS*, **487**, 2594, 2019.

Galactic Archaeology with *Gaia*

By GyuChul Myeong

The halo of our Galaxy is believed to be mainly formed by the materials accreted/merged in the past, and so has an ‘extragalactic’ origin. Such a formation process will leave dynamical traces imprinted in the halo, like stellar substructures, distinguishable from the *in-situ* halo component. Studying the present-day structure and substructures of the Milky Way halo is one of the most direct ways of understanding the formation and the evolutionary history of the Galaxy, as well as investigating the ΛCDM model on the galaxy scale which has not yet been tested thoroughly. It has been a challenge to obtain a sufficiently large sample of halo stars for such study due to the sparse density of the halo. The recent *Gaia* mission can open a new era for the study of Galactic archaeology as it provides high-quality data for $\sim 1{\cdot}3$ billion stars across the Milky Way which had remained uncharted so far.

In Chapter 1, I describe a history of study on the Milky Way halo so far, and present algorithms that are developed to investigate the substructures of the halo with various aspects.

Chapter 2 is a morphological study of the Milky Way halo based on the chemo-dynamical information. It reveals various interesting aspects of the halo and its origin, such as the chemo-dynamical duality (evidence of a past major merger — the ‘Gaia Sausage’), traces of a past retrograde accretion (clues as to the origin of the retrograde halo component), and the resonant feature (evidence of dynamical influence of the Milky Way bar).

Chapters 3, 4, and 5 are examples of a more focussed study on the halo substructures with various new methods that differ from the conventional studies. In addition to the discovery of new stellar streams, I investigate the properties of the potential progenitors (past accreted dwarf galaxies) of these substructures, and also the potential association with ω Centauri.

Chapter 6 is a study investigating the potential extragalactic origin of the Milky Way globular clusters based on their dynamics and various other information, such as age, metallicity, and horizontal-branch index. It reveals a collection of globular clusters with extragalactic origin, originating from the 'Gaia Sausage'.

Chapter 7 is a chemo-dynamical study showing the evidence for another early accretion event — the 'Sequoia'. From multiple tracers in the Milky Way halo, including the stellar streams and globular clusters, I investigate the dynamical and the chemical signature of the 'Sequoia' progenitor and its present-day remnants. — *University of Cambridge; accepted 2019 July*.

Black-Hole Feedback in New Regimes: Modelling Dwarf Galaxies with Active Galactic Nuclei

By Sophie Koudmani

Contrary to the standard lore, there is mounting observational evidence that feedback from active galactic nuclei (AGN) may also play a role at the low-mass end of the galaxy population. In this thesis, I explore that possibility employing both isolated and cosmological simulations of dwarf galaxies.

Firstly, I perform high-resolution simulations of isolated dwarf galaxies. In these simulations, the AGN has only a limited direct effect on star-formation rates. There is, however, a significant effect on outflows, which are notably enhanced by the AGN to much higher temperatures and velocities. This indicates that AGN may play an indirect role in quenching dwarf galaxies by hindering cosmic gas inflows.

I further investigate this quenching scenario using the cosmological simulation suite FABLE. While in the local Universe the majority of AGN in dwarfs are much dimmer than the stellar component, for $z \geq 2$ there is a significant population of AGN that outshine their hosts. These high-redshift over-massive black holes contribute to the quenching of dwarfs, whereas at late cosmic times supernova (SN) feedback is more efficient. However, the lack of high-luminosity X-ray AGN in FABLE at low redshifts highlights an interesting possibility that SN feedback could be too strong in FABLE's dwarfs, curtailing AGN growth and feedback.

To examine the interplay between SNe and AGN accretion in more detail, I run a series of cosmological zoom-in simulations. I find that AGN feedback in tandem with more realistic SN feedback can be a successful alternative quenching mechanism to strong SN feedback in dwarfs, provided that the AGN is able to enter the high-accretion regime for at least part of its history. However, the Bondi rate generally prevents low-mass black holes from accreting efficiently, even though sufficient amounts of gas are available in these dwarfs.

Finally, I present a more robust AGN accretion model based on a unified accretion disc, which combines the ADIOS flow and standard thin-disc schemes.

This model will allow for the self-consistent exploration of the high-accretion regime in dwarf galaxies and detailed modelling of multi-messenger signatures, in preparation for the next-generation electromagnetic and gravitational-wave observatories. — *University of Cambridge; accepted 2021 September.*

Cosmology from Galaxy Clusters with Cosmic Microwave Background Lensing-Mass Calibration

By Íñigo Zubeldia

In this thesis, we present a cosmological analysis of the galaxy clusters in the *Planck* MMF3 cosmology sample, which consists of 439 Sunyaev–Zel'dovich-detected clusters, with a cosmic microwave background (CMB) lensing calibration of the cluster masses. As demonstrated by *Planck*, galaxy clusters detected through their SZ signature offer a powerful way to constrain cosmological parameters such as Ω_m, which parametrizes the mean matter density of the Universe, and σ_8, which characterizes the amplitude of the matter perturbations. Determining the absolute cluster mass scale is, however, difficult, and some recent calibrations have yielded cosmological constraints in apparent tension with constraints in the ΛCDM model derived from the power spectra of the primary CMB anisotropies.

In order to calibrate the absolute mass scale of the full *Planck* cluster sample, we measure the CMB lensing signals of 433 of its clusters (those with measured redshift) with *Planck* temperature data. We calibrate the bias and intrinsic scatter of our CMB lensing mass observable, the CMB lensing signal-to-noise, with mock observations from an N-body simulation. We then perform a joint likelihood analysis of the cluster counts and mass observables taking as input the CMB lensing signal-to-noise ratios, SZ signal-to-noise ratios, and redshifts. Our analysis uses a likelihood that properly accounts for selection effects in the construction of the cluster sample. We find $\sigma_8\ (\Omega_m/0{\cdot}33)^{0{\cdot}25} = 0{\cdot}765 \pm 0{\cdot}035$, $\Omega_m = 0{\cdot}33 \pm 0{\cdot}02$, $\sigma_8 = 0{\cdot}76 \pm 0{\cdot}04$, and $1 - b_{SZ} = 0{\cdot}71 \pm 0{\cdot}10$, where the mass bias factor $1 - b_{SZ}$ relates cluster mass to the SZ mass that appears in the X-ray-calibrated cluster scaling relations. We find no evidence for tension with the *Planck* primary CMB constraints on ΛCDM model parameters. — *University of Cambridge; accepted 2020 April.*

CORRIGENDUM

On p. 317 of the 2021 December issue, it was first stated (for 1722 June 29) that Captain Bartholomew Candler observed a lunar eclipse. However, on 1722 November 2 it was sadly pointed out that Captain Benjamin Candler had died. They were one and the same person whose first name was Bartholomew. The Editors and Kenelm England apologise for this confusion.

Here and There

FLY ME TO THE MOON

The crew will fly higher than any humans since the Space Shuttle missions to the Moon. — *Independent*, 2021 September 16th.

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