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ANCIENT REPORTS OF THE ZODIACAL LIGHT AS VIEWED FROM MOUNTAIN TOPS

By Marinus Anthony van der Sluijs

Different perspectives on a drawn-out twilight

The Caucasus is a mountain system stretching between the Black Sea and the Caspian Sea. Connecting Europe and Asia, many of its peaks reach altitudes in excess of 4000 m. One of these, Elbrus, is considered to be the highest in Europe, at 5642 m. Aristotle (384–322 BC; *Meteorology*, 1.13 [350a]) conveyed the curious information that the Caucasus' vertiginous height exposed it to sunlight for several more hours than its surroundings: "The Caucasus is the largest mountain, both in extent and height, towards the summer sunrise. A proof of its height is the fact that it is visible both from the so-called Deeps and also as you sail into the lake; and also that its peak is sunlit for a third part of the night, both before sunrise and again after sunset"[1]. The words "towards the summer sunrise" (*pròs tȇn héō tȇn therinḗn*) are a parochial indication of place, correctly situating the Caucasus to the northeast of Greece. The 'Deeps' (*bathéōn*) were the 'deeps of Pontus' (*bathéa tou Póntou*) (Aristotle, *Meteorology*, 1.13 [351]). The lake is either Lake Maeotis, now the Sea of Azov, or the Caspian Sea[2].

At first glance, the extended illumination of the Caucasus' peaks matches the Alpenglow — a roseate light crowning mountains when the Sun is just below the horizon. However, sunrays do not strike even the highest peaks through any significant portion of the night, whether 'night' is defined as the period between civil, nautical, or astronomical twilights. It has been calculated that the Caucasus would have to be 5760 km high in order to meet Aristotle's description[3]. Yet before dismissing the latter as an exaggeration, it may be worth posing this fundamental question: was the light effect seen from afar? Reading closely, Aristotle only explicitly distanced observers from the mountain for the daytime settings on the water, not for the nighttime visibility. A revealing perspective on what could be the same phenomenon is afforded by the account that Pliny the Elder (AD *c.* 23–79; *Natural History*, 5.18 [80]) gave of Mount Casius: "… Casius, which is so extremely lofty that in the fourth quarter of the night it commands a view of the sun rising through the darkness, so presenting to the observer if he merely turns round a view of day and night simultaneously. The winding route to the summit measures 19 miles, the perpendicular height of the mountain being 4 miles"[4]. Spelling 'Cassius', the grammarian and geographer Solinus (3rd century AD; *Collection of Curiosities*, 36.3) repeated:

"… Mount Cassius … from the summit of which the orb of the sun is visible from the fourth watch of the night, and with a slight twist of the body — as the rays dissipate the gloom — one can see night on one side, day on the other. Such is the view from Cassius that you can already see the light before the day begins"[5]. Called Saphon in the Bible and Ğebel al-Aqra‘ in Arabic, Casius is located on the Syrian–Turkish border. Here, according to Pliny and Solinus, day breaks much earlier than elsewhere, but as seen from the top of the mountain, not from a valley east of it. Perhaps this was also the import of the Aristotelian passage.

Owing to atmospheric refraction, sunrise normally appears to take place slightly earlier than its actual occurrence. Under exceptional circumstances, a category of mirage called the Novaya Zemlya effect can cause the apparent sunrise to happen much earlier still[6]. This is more pronounced at polar latitudes, however; at middle latitudes, the difference would only be a matter of seconds to minutes — a far cry from the multiple hours implied by the sources examined so far, which also suggest a more regular phenomenon. If, then, the Alpenglow and mirages fall short, what could be behind the ancient reports?

The zodiacal light

The zodiacal light is sunlight reflected off a cloud of dust particles in the inner Solar System. These straddle the ecliptic, defined by the plane of the Earth's orbit around the Sun. Consequently, the light is concentrated in the zodiac as seen from Earth and this gives it its name. At mid-northern latitudes, it typically appears as a tilted cone above the horizon in the direction of the Sun some time before sunrise in autumn and after sunset in spring — the so-called 'false dawn' and 'false dusk'. The sight of an imposing luminous cone on the eastern side of the sky while the west remains shrouded in darkness, nothing like the normal dawn, could easily have imbued a sense that day and night were present at once, as reported for Casius. It is well known that the purity of air and the absence of light pollution up in the mountains are highly conducive to seeing this dim light. Ignorant of its true nature, the Earth's size, and the distance to the Sun, someone beholding it from the top of a mountain could readily have inferred that not the rarefied air but the mountain's height facilitated its appearance. That may even have led some to imagine falsely that people at ground level, too, can see the eastern flank of the mountain top lit up hours before sunrise or the western one hours after sunset.

Circumstantial support for this interpretation of the ancient testimony comes from the fact that Islamic cosmographers were well aware of the 'false dawn' (*ṣubḥ-i kāẕib*) and sometimes involved the Caucasus in their explanation of it. In their worldview, Qāf — the Arabic name for this mountain range — encircled the entire flat Earth, at such a distance that its peaks do not rise above the horizon of the civilized world. Edward Warren Hastings Scott-Waring (1783–1821) was a Bengal civil servant who frequently observed the false dawn during his sojourn in Persia and India. This experience prompted him to relay the following piece of Persian folklore: "They account for this phenomenon in a most whimsical manner. They say, that as the sun rises from behind the Kohi Qaf (Mount Caucasus), it passes a hole perforated through the mountain, and that darting its rays through it, it is the cause of the *Soobhi Kazim*, or this temporary appearance of day-break. As it ascends the earth is again veiled in darkness, until the sun rises above the mountain, and brings with it the *Soobhi Sadiq*, or real morning"[7]. If people in the Middle East associated the zodiacal light with legendary properties of the Caucasus as late as the 18th or 19th

Century, it stands to reason that they could have done so long before, be it in different ways — with the mountain being nearer and sunlight from below the local horizon shining onto its top rather than through it. Reaching even further back in time than Aristotle, it has also been suggested that the zodiacal light was itself represented by Māšu, the twin mountain of Babylonian myth which led Gilgameš along the "path of the sun" to the spirit land beyond[8].

An 'Idaeal' view

There is a third Anatolian mountain for which a strikingly long twilight was reported in antiquity: Mount Ida in the Troad (northwestern Turkey). With emphasis again on the view from the peak, not of the peak, a smattering of authors reported that an observer could watch scattered 'flames' combine and contract to form the rising Sun. Thus Diodorus of Sicily (*fl.* 1st century BC; *Historical Library*, 17.7.5–7): "There is a singular and strange phenomenon associated with this mountain: at the time of the rising of the Dog Star, on the highest peak by the stillness of the surrounding air the peak gives the impression of being elevated above the swirling of the winds, and the sun is seen to rise while it is still night, with its rays not concentrated into a circular shape, but with its fire scattered in many places, so that it looks as though many fires touch the Earth's horizon. Then, a short while later, these draw together into one quantity with a diameter of three plethra. And finally, once day has dawned, the sun's manifest size is attained and produces the condition of the daytime"[9]. In this account, the spectacle features an intermediate stage in which the many scattered flames merge into 'one quantity' (*hèn mégethos*) with an apparent width of about 90 m — a *plethron* corresponding to *c.* 30 m — before the ordinary solar disc congeals.

A Roman contemporary of Diodorus, Lucretius (*c.* 99–*c.* 55 BC; *On the Nature of Things*, 5.656–665) integrated the anomaly of Ida into his didactic poem on nature: "At a fixed time also Matuta diffuses the rosy dawn through the regions of ether and spreads out her light, either because the same sun returning under the earth takes his first hold on the sky as he tries to kindle it with his rays, or because there is a gathering together of fires, and many seeds of heat are accustomed to flow together at a fixed time, which make each day the light of a new sun arise: just as it is said that from the lofty mountain of Ida at sunrise scattered fires are seen, and then as it were these gather together into one globe and together form an orb"[10]. Here, Lucretius cites the observation from Ida as evidence for a theory that the Sun does not travel continuously around the Earth but is produced anew every morning by the convergence of many small fires. This was the contention of Xenophanes of Colophon (*c.* 570–*c.* 478 BC)[11]. Heraclitus of Ephesus (*c.* 535–*c.* 475 BC), too, taught that the Sun is new every day (Aristotle, *Meteorology*, 2.2 [355a]), but that was a case of renewal by rekindling rather than a fresh creation (scholiast on Plato's *Republic*, 498a)[12].

In his *Description of the World* (1.18 [94–95]), published around AD 43, the Roman geographer Pomponius Mela elaborated on the same marvel, informing that it would begin around midnight: "The mountain itself … reveals the rising sun differently from the way it is usually viewed in other lands. In fact, for people watching from the very peak, more or less from the middle of the night on, scattered fires appear to shine. The nearer the light draws, the more those fires appear to come together and to fuse with one another, until, as a result of being gathered closer and closer together, fewer fires are burning, and until, at the end, they burn with a single flame. After that light has blazed brilliantly, like a fire, for a long time, it compresses itself, becomes round, and turns into a huge sphere. For a long time that sphere appears sizable and tied to the earth. Then it decreases little by little, becoming brighter the more it decreases. Last of all, it dispels the night, and, turning into the sun now, it rises along with the day"[13]. Pliny (*Natural History*, 2.8 [50]) touched on the subject, too, when dealing with the Sun's size: "… when it is rising its breadth exceeds Mount Ida, overlapping it widely right and left — and that though it is separated from it by so great a distance"[14]. More tersely still, Solinus (*Collection of Curiosities*, 11.7) remarked that Ida "sees the sun before sunrise"[15], but he believed this to concern the mountain's namesake on Crete. This will have been an error on his part.

Ultimately, these writers were probably all drawing on a single literary source that is not extant. A 19th-Century scholar fingered the historian Ephorus of Cyme (*c.* 400–330 BC) as the one on whom Diodorus and Mela relied[16]. While that may be so, the tradition must be at least as old as 415 BC, when the famous tragedian Euripides (*Trojan Women*, 1069) portrayed Mount Ida as "the boundary first struck by the sun" (*térmona te prōtóbolon halíō*)[17]. Xenophanes' place of birth was in western Asia Minor, just over 100 km south of Ida. Could it not be the very scene on Ida that inspired his quirky theory of the Sun in the first place? That much was proposed in 1894 by the French Egyptologist Eugène Lefébure (1838–1908), who adduced the passages from Lucretius, Diodorus, and Mela[18]. More recently, his Hellenist compatriot Paul Goukowsky attributed Diodorus' information to Cleostratus of Tenedos[19], an astronomer known to have made observations from Ida[20], which can indeed be seen from his native island. Goukowsky was oblivious to the parallel passage in Lucretius, which surely alludes to Xenophanes. However, given that Cleostratus' *floruit* is usually dated to the late 6th Century BC but exact dates are unknown, it seems possible that Xenophanes drew on his observations as he formulated his solar theory.

Dead ends

In a lecture he gave to Paris' Académie Royale des Inscriptions et Belles-Lettres on 1754 November 19, Jean-Jacques d'Ortous de Mairan (1678–1771) argued that the goings-on at Ida, as told by Diodorus, were displays of the *aurora borealis* viewed over its top from a location to its south[21]. Considering also that the northern lights would be expected to appear sporadically and in a northern direction, this interpretation conflicts with the textual evidence that the phenomenon was seen upon ascent of the mountain, regularly and culminating in the direction of sunrise. In auroral terms the gathering of the 'flames' would have to be a corona, seen when the auroral oval passes through the zenith, yet the type of aurora showing at Mediterranean latitudes is generally no more spectacular than a diffuse red glow or stable arc over the horizon. Also, aurorae are potentially visible at any time of the night, with a general focus on the hours around midnight. By contrast, the 'strange sunrise' at Ida was confined to the latter half of the night, ending in sunrise.

Goukowsky saw in the cited passages a reference to parhelia followed by a halo, the Bosporus apparently being favourable for parhelia[22]. This is not tenable either. While these optical effects are indeed most common when the Sun is near the horizon, they require that at least a part of the Sun be above the horizon (Aristotle, *Meteorology*, 3.2 [372a]) — and yet the lights at Ida manifested during the nighttime, even as early as midnight. Haloes and parhelia, also known as sun dogs, are concurrent with the Sun and do not 'transform' into it — unlike the stable "huge sphere" (*ingens globus*) towards the end of the sequence at Ida, that shrank and brightened to become the Sun. That 'sphere' was perhaps nothing more than the arc of rosy twilight seen when the sky is still quite dark, at the onset of the true dawn. Equally incompatible with a halo is that the 'sphere' formed from 'one quantity' or 'single flame' that, in Mela's words, "becomes round" (*rotundat*) and thus must have had a very different shape.

In Goukowsky's view, the parhelia at Ida were "singular and strange" because no one before Anaxagoras (*c.* 500–*c.* 428 BC) attempted to explain parhelia. Yet, apart from the fact that the quoted sources all postdate Anaxagoras, wouldn't the Greeks have been familiar with parhelia from other places and have had a word for them anyway?

As a final objection, Diodorus timed the event to the rising of the Dog Star. This is doubtless the heliacal rising of Sirius. The heliacal rising of a celestial body is the annual occasion when it first becomes visible above the eastern horizon at dawn, just before sunrise. That of Sirius was historically the most important one, notably in Egypt. Taking axial precession into account, it transpired at 18–20 July in classical times[23]. According to Goukowsky, the point was that the calm weather prevailing during these dog days increased the likelihood of sun dogs. Perhaps this seasonal tranquility of air provided the Greeks with a rationale for the annual timing of whatever the mountain's great altitude enabled men to see, but parhelia are not bound to any particular season.

Nor is confusion with the Milky Way plausible. It is too static to suggest any convergence of flames, bears no special relationship to sunrise or Sirius' heliacal rising, and was too familiar to the ancients to evade recognition.

Joining the dots

It is surprising that d'Ortous de Mairan settled for the aurora, as this savant was renowned for his pioneering work on that as well as the zodiacal light. The long-lived mass into which the scattered 'flames' coalesce before the appearance of the normal solar orb is arguably the characteristic cone of the zodiacal light. This has actually been claimed, but apparently only once and long ago — by Lefébure[24]. The suggestion did not catch on and deserves now to be revived.

If Ida's dispersed 'fires' appeared on the exact days of Sirius' heliacal rising, the star would only have risen after their merger into the light of the true dawn. It is perfectly conceivable that Diodorus meant to indicate the beginning of a longer period, in which Sirius would eventually rise much earlier. That would be the time of year which Homer (*Iliad*, 5.5–6) poetically hinted at with the words "the star of harvest-time that shines brightest of all others when he has bathed in the stream of Ocean"[25]. D'Ortous de Mairan, who made this connection, seized on it to prop up his auroral explanation, but whereas northern lights are as likely in the spring as in the autumn, late summer is the season *par excellence* for the zodiacal light's pre-dawn appearance.

The scattered 'flames' that precede the phase of a single light, as seen from Ida, obviously involve more than just the classic cone of zodiacal light. The cone is only the most iconic component of a whole complex of forms that, to be fair to d'Ortous de Mairan, had not yet been described in his day. On the opposite side of the sky to the main cone, atmospheric backscattering can produce a dimmer or smaller cone known as the false zodiacal light[26]. Backscattering off interplanetary dust outside the Earth's orbit is the cause of a diffuse glow called the *Gegenschein*, which is German for 'countershine' or 'counterglow'. Situated exactly at the antisolar point, its position changes with the Sun's invisible passage below the horizon. Best seen around midnight, when it appears highest in the sky, in months when it is not in front of the Milky Way[27], it varies in shape from "small and somewhat elongated" to "very large and round"[28]. The zodiacal band is sunlight reflected off dust outside the Earth's orbit that forms a narrow extension from a cone along the ecliptic. It is fainter still than the *Gegenschein*, which it flanks when seen together. Naturally, these features are most conspicuous in a clear, moonless sky. They are not as elusive as is widely believed, however[28].

In addition to this family of zodiacal-light phenomena, eyes fully adapted to very dark and clear skies should be able to see patches of airglow. This is a faint background luminosity to the sky, mainly produced by ultraviolet radiation in sunlight exciting atoms and molecules in the atmosphere; this process of photoionization is different from the excitation by charged particles from the solar wind, which causes the aurora. Airglow, or nightglow in this case, can exhibit some slowly changing structure, but is fairly uniform through the atmosphere. It appears brightest at about 10° above the horizon because of the greater depth of atmosphere an observer looks through at that level; further down, atmospheric extinction renders it invisible. This is consistent with Diodorus' mention of fires that "touch the earth's horizon".

Conjointly, airglow and the zodiacal-light complex offer a compelling explanation for the display of lights atop Ida. As argued, the cases of Casius and Caucasus can be seen in the same — zodiacal — light. A consistent impression emerges of Anatolian mountains renowned for the protracted 'dawn' perceived from their tops. Reminded of the contemporary practice of tourists scaling popular peaks for a sunrise experience, Lefébure suspected that the zodiacal light may have acted as a similar draw in ancient times. It may be rewarding to put the present argument to the test by visiting these mountains.

The zodiacal light, let alone the associated features, has been notoriously hard to detect in classical texts, or any ancient documents. It is, therefore, of considerable interest for the history of astronomy that the Graeco-Roman authors cited above should have unwittingly testified to these fascinating glows in the night sky. In retrospect, their take was not even all that far-fetched. They discovered the benefit of elevated vantage points and, airglow aside, correctly intuited the lights' correlation with the Sun's whereabouts.

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GSC 03937-02349: A SHORT-PERIOD W UMA BINARY WITH A MASSIVE COMPANION

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The saw-tooth pattern seen in the O–C residuals of GSC 03937-02349 is attributed to the effect of a third body in the system in a circular orbit with $P_3 = 3{\cdot}87 \pm 0{\cdot}03$ yr. The short period and light-travel time $A = 0^{\rm d}{\cdot}00765(14)$ combine to suggest a minimum mass of the companion $m_3 = 0{\cdot}95\ M_{\odot}$. Such a large mass is comparable to the likely mass of the primary component of the W UMa star, or it may be a binary in its own right. The companion probably contributes 70% of the luminosity of the system.

Close binary stars are frequently found in multiple systems[1,2], with the proportion of those with close companions ranging from at least 20%[3] to about 60%[4,5] for short-period systems. From a sample of 700 systems Latković *et al.*[3] found the median third-body period P_3 = 10 years and there are 12 systems listed with P_3 between 2 and 5 years. However, the best observed is probably the quadruple system, VW LMi, which has a 2+2 hierarchy with a $0^{\rm d}{\cdot}477$ W UMa eclipsing binary and another non-eclipsing $7^{\rm d}{\cdot}93$ binary in a 355-day orbit[6]. Companions of W UMa binaries range from low-mass ($m_3 \sim 0{\cdot}15\ M_{\odot}$) third bodies, *e.g.*, AM Leo[7], YY Eri[8], through intermediate, *e.g.*, V523 Cas[9], and relatively high-mass ($m_3 \sim 0{\cdot}8\ M_{\odot}$) companions, *e.g.*, VW Cep[10], ER Ori[11], to quadruple systems with the 2+2 hierarchy, *e.g.*, TZ Boo, V2610 Oph[2], and VW LMi[6], where the two binaries are of comparable mass.

GSC 03937-02349 (UCAC4 715-069519, $20^h\ 17^m\ 01^s{\cdot}176$ $+52°\ 52'\ 40''{\cdot}78$ *Gaia* DR3) was found to be a low-amplitude eclipsing binary by Frank in 2009* while observing the nearby 14th-magnitude EA/DS eclipsing binary V1047 Cyg. The star was not observed again until 2016 when the initial ephemeris was published by Moschner *et al.*[12] (where it is referred to as MoFr22 Cyg) and showed that the star is a short-period, low-amplitude W UMa system. A period of $0^d{\cdot}2875$ places the system at the cool, low-mass end of the W UMa distribution, and the depths of the eclipses at $0^m{\cdot}15$ and $0^m{\cdot}13$ suggest that the inclination is not high. Time-series observations then continued every season from 2016, and recently Moschner *et al.*[13] published a study of the eclipse timings which showed a saw-tooth pattern of the O–C residuals with an amplitude of $\pm 0^d{\cdot}01$ and a period of about four years. The most likely interpretation of the timing data is that the residuals are due to action of a third body on the W UMa binary. Further observations were made in 2022 leading to a total of 33 runs containing 54 eclipses. The times of minimum have been redetermined using the Kwee–van Woerden method in order to estimate the uncertainties. However, the timings are not identical to those of Moschner *et al.* due in part to differences in the data selected for each minimum but also because of a difference between HJD(UT) and HJD(TT), which means that on average these timings are about 69 seconds later than those published previously. The times of minimum are collected in Table I with the others determined later. Phase diagrams for the best runs from 2018 and 2020 are shown in Fig. 1 with a 4-harmonic Fourier fit indicating the mean light-curve. The season-to-season variation in the maxima is small, so there is no clear and persistent O'Connell effect[14,15].

GSC 03937-02349 has a mean $G = 13{\cdot}23$ and lies in a relatively crowded field with a star three magnitudes brighter at a distance of 43 arcsec, and two other stars with $G \sim 14{\cdot}5$ within that radius, one of which, UCAC3 286-155544 = MoFr21 Cyg, is also variable[12]. A search for other photometry from the synoptic surveys showed that the *TESS* data[16], the *SuperWASP* data[17], and the Northern Variability Sky Survey data[18] are all corrupted by the nearby bright star. However, the separation is sufficiently large that the All-Sky Automated

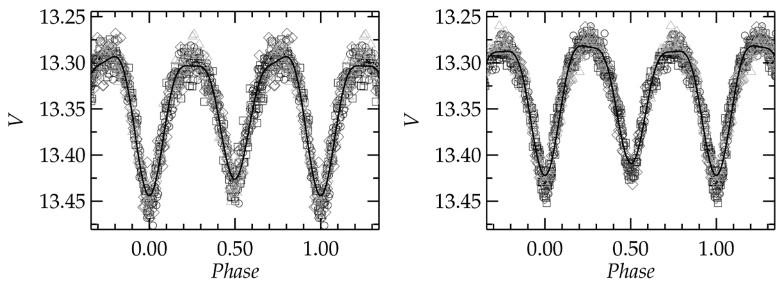

Fig. 1

Phase diagrams of the best time-series runs from 2018 and 2020. A 4-harmonic Fourier fit indicates the mean light-curve. The mean dispersion of the fit is typically $0^m{\cdot}011$ and the small but significant difference between the two minima can be seen. The scatter around the maxima makes it difficult to make a definitive judgement about an O'Connell effect, but if present then it is relatively small.

*VSX entry https://www.aavso.org/vsx/index.php?view=detail.top&oid=477670

TABLE I

Time of Minimum

HJD	*Error*	*Min.*	*Cycle*	*O–C (d) Linear*	*O–C (d) LTTE*	*Band*	*Observer/Source*
2455333·4255	0·0004	2	−7902·5	0·0049	0·0001	*C*	Frank (This paper)
2455345·9352	0·0033	1	−7859·0	0·0083	0·0031	*W* 1	*WISE* (This paper)
2455345·9364	0·0027	1	−7859·0	0·0094	0·0043	*W* 2	*WISE* (This paper)
2455346·0743	0·0038	2	−7858·5	0·0036	−0·0015	*W* 1	*WISE* (This paper)
2456874·8727	0·0016	1	−2541·0	0·0061	−0·0012	*V*	ASAS-SN (This paper)
2456875·0157	0·0015	2	−2540·5	0·0054	−0·0019	*V*	ASAS-SN (This paper)
2457229·0734	0·0010	1	−1309·0	0·0034	0·0010	*V*	ASAS-SN (This paper)
2457229·2173	0·0010	2	−1308·5	0·0035	0·0012	*V*	ASAS-SN (This paper)
2457574·4978	0·0005	2	−107·5	−0·0068	0·0004	*C*	Moschner (This paper)
2457574·6389	0·0008	1	−107·0	−0·0094	−0·0022	*C*	Moschner (This paper)
2457576·5086	0·0005	2	−100·5	−0·0084	−0·0012	*C*	Moschner (This paper)
2457581·5396	0·0005	1	−83·0	−0·0088	−0·0015	*C*	Moschner (This paper)
2457582·9800	0·0010	1	−78·0	−0·0059	0·0014	*V*	ASAS-SN (This paper)
2457583·1233	0·0014	2	−77·5	−0·0063	0·0010	*V*	ASAS-SN (This paper)
2457605·4028	0·0004	1	0·0	−0·0083	−0·0008	*C*	Moschner (This paper)
2457605·5463	0·0008	2	0·5	−0·0085	−0·0011	*C*	Moschner (This paper)
2457617·7687	0·0011	1	43·0	−0·0050	0·0025	o	*ATLAS* (This paper)
2457617·9095	0·0010	2	43·5	−0·0079	−0·0004	o	*ATLAS* (This paper)
2457623·3710	0·0007	2	62·5	−0·0091	−0·0015	*C*	Moschner (This paper)
2457623·5140	0·0004	1	63·0	−0·0098	−0·0022	*C*	Moschner (This paper)
2457625·8147	0·0012	1	71·0	−0·0091	−0·0015	*c*	*ATLAS* (This paper)
2457625·9624	0·0010	2	71·5	−0·0051	0·0025	*c*	*ATLAS* (This paper)
2457691·3665	0·0005	1	299·0	−0·0080	−0·0004	*V*	Moschner (This paper)
2457916·6289	0·0006	2	1082·5	−0·0039	−0·0009	*V*	Moschner (This paper)
2457921·0855	0·0012	1	1098·0	−0·0036	−0·0008	*V*	ASAS-SN (This paper)
2457921·2275	0·0013	2	1098·5	−0·0054	−0·0026	*V*	ASAS-SN (This paper)
2457955·4442	0·0007	2	1217·5	−0·0015	0·0002	*V*	Moschner (This paper)
2457955·5887	0·0006	1	1218·0	−0·0008	0·0009	*V*	Moschner (This paper)
2457963·4939	0·0005	2	1245·5	−0·0019	−0·0004	*V*	Moschner (This paper)
2457963·6383	0·0004	1	1246·0	−0·0013	0·0002	*V*	Moschner (This paper)
2457979·4512	0·0005	1	1301·0	−0·0010	−0·0001	*V*	Moschner (This paper)
2457979·5963	0·0005	2	1301·5	0·0004	0·0013	*V*	Moschner (This paper)
2458002·7411	0·0006	1	1382·0	0·0012	0·0013	o	*ATLAS* (This paper)
2458002·8843	0·0007	2	1382·5	0·0006	0·0007	o	*ATLAS* (This paper)
2458004·4652	0·0013	1	1388·0	0·0002	0·0003	*V*	Moschner (This paper)
2458010·3592	0·0005	2	1408·5	0·0004	0·0003	*V*	Moschner (This paper)
2458010·5033	0·0007	1	1409·0	0·0008	0·0006	*V*	Moschner (This paper)
2458015·3913	0·0005	1	1426·0	0·0013	0·0010	*V*	Moschner (This paper)
2458015·5334	0·0015	2	1426·5	−0·0004	−0·0008	*V*	Moschner (This paper)
2458277·8859	0·0009	1	2339·0	0·0058	−0·0013	*V*	ASAS-SN (This paper)
2458278·0292	0·0011	2	2339·5	0·0054	−0·0018	*V*	ASAS-SN (This paper)
2458321·0110	0·0009	1	2489·0	0·0055	−0·0020	*zg*	*ZTF* (This paper)
2458321·1566	0·0013	2	2489·5	0·0074	−0·0002	*zg*	*ZTF* (This paper)
2458329·4968	0·0006	2	2518·5	0·0100	0·0024	*V*	Moschner (This paper)
2458329·6367	0·0007	1	2519·0	0·0061	−0·0015	*V*	Moschner (This paper)
2458330·5009	0·0006	1	2522·0	0·0078	0·0002	*V*	Moschner (This paper)
2458330·6444	0·0008	2	2522·5	0·0076	0·0000	*V*	Moschner (This paper)
2458352·3523	0·0007	1	2598·0	0·0091	0·0014	*V*	Moschner (This paper)
2458352·4949	0·0005	2	2598·5	0·0079	0·0002	*V*	Moschner (This paper)
2458367·0143	0·0005	1	2649·0	0·0084	0·0007	*o*	*ATLAS* (This paper)
2458367·1568	0·0007	2	2649·5	0·0072	−0·0004	*o*	*ATLAS* (This paper)
2458396·9136	0·0012	1	2753·0	0·0074	−0·0001	*c*	*ATLAS* (This paper)
2458397·3458	0·0005	2	2754·5	0·0084	0·0008	*V*	Moschner (This paper)
2458397·4885	0·0006	1	2755·0	0·0073	−0·0002	*V*	Moschner (This paper)
2458441·9073	0·0005	2	2909·5	0·0069	−0·0002	*zr*	*ZTF* (This paper)
2458630·9365	0·0007	1	3567·0	0·0031	0·0003	*g*	ASAS-SN (This paper)
2458631·0804	0·0009	2	3567·5	0·0032	0·0005	*g*	ASAS-SN (This paper)
2458716·8955	0·0007	1	3866·0	−0·0012	−0·0011	*o*	*ATLAS* (This paper)
2458717·0397	0·0010	2	3866·5	−0·0008	−0·0007	*o*	*ATLAS* (This paper)

TABLE I (continued)

HJD	*Error*	*Min.*	*Cycle*	*O–C (d) Linear*	*O–C (d) LTTE*	*Band*	*Observer/Source*
2458720·3475	0·0006	1	3878·0	0·0008	0·0010	*V*	Moschner (This paper)
2458720·4912	0·0004	2	3878·5	0·0006	0·0009	*V*	Moschner (This paper)
2458720·6340	0·0007	1	3879·0	−0·0003	−0·0000	*V*	Moschner (This paper)
2458720·9210	0·0015	1	3880·0	−0·0008	−0·0005	*c*	*ATLAS* (This paper)
2458726·6715	0·0005	1	3900·0	−0·0004	0·0001	*zr*	*ZTF* (This paper)
2458726·8164	0·0006	2	3900·5	0·0008	0·0013	*zr*	*ZTF* (This paper)
2458732·7084	0·0007	1	3921·0	−0·0010	−0·0003	*zg*	*ZTF* (This paper)
2458732·8533	0·0009	2	3921·5	0·0002	0·0008	*zg*	*ZTF* (This paper)
2458755·4211	0·0004	1	4000·0	−0·0010	0·0004	*V*	Moschner (This paper)
2459039·7571	0·0010	1	4989·0	−0·0053	0·0023	*g*	ASAS-SN (This paper)
2459039·8999	0·0010	2	4989·5	−0·0062	0·0014	*g*	ASAS-SN (This paper)
2459049·0996	0·0015	2	5021·5	−0·0066	0·0010	*c*	*ATLAS* (This paper)
2459049·2407	0·0018	1	5022·0	−0·0092	−0·0016	*c*	*ATLAS* (This paper)
2459053·4100	0·0007	2	5036·5	−0·0087	−0·0011	*V*	Moschner (This paper)
2459053·5545	0·0005	1	5037·0	−0·0080	−0·0003	*V*	Moschner (This paper)
2459069·3669	0·0008	1	5092·0	−0·0082	−0·0006	*V*	Moschner (This paper)
2459069·5109	0·0005	2	5092·5	−0·0080	−0·0003	*V*	Moschner (This paper)
2459069·6529	0·0005	1	5093·0	−0·0097	−0·0021	*V*	Moschner (This paper)
2459071·9542	0·0009	1	5101·0	−0·0084	−0·0008	*zr*	*ZTF* (This paper)
2459072·0987	0·0012	2	5101·5	−0·0078	−0·0001	*zr*	*ZTF* (This paper)
2459072·8177	0·0012	1	5104·0	−0·0075	0·0002	*zg*	*ZTF* (This paper)
2459072·9623	0·0010	2	5104·5	−0·0066	0·0010	*zg*	*ZTF* (This paper)
2459082·8813	0·0008	1	5139·0	−0·0065	0·0011	*o*	*ATLAS* (This paper)
2459083·0252	0·0008	2	5139·5	−0·0063	0·0013	*o*	*ATLAS* (This paper)
2459102·4295	0·0005	1	5207·0	−0·0084	−0·0009	*V*	Moschner (This paper)
2459102·5745	0·0007	2	5207·5	−0·0072	0·0004	*V*	Moschner (This paper)
2459140·3817	0·0008	1	5339·0	−0·0066	0·0006	*V*	Moschner (This paper)
2459403·5953	0·0005	2	6254·5	−0·0018	−0·0013	*V*	Moschner (This paper)
2459404·8907	0·0018	1	6259·0	−0·0001	0·0004	*c*	*ATLAS* (This paper)
2459405·0346	0·0014	2	6259·5	−0·0000	0·0004	*c*	*ATLAS* (This paper)
2459406·9042	0·0008	1	6266·0	0·0008	0·0012	*zr*	*ZTF* (This paper)
2459407·0460	0·0009	2	6266·5	−0·0011	−0·0007	*zr*	*ZTF* (This paper)
2459408·9169	0·0012	1	6273·0	0·0010	0·0013	*zg*	*ZTF* (This paper)
2459409·0577	0·0016	2	6273·5	−0·0019	−0·0016	*zg*	*ZTF* (This paper)
2459423·5795	0·0007	1	6324·0	0·0010	0·0008	*g*	ASAS-SN (This paper)
2459423·7225	0·0008	2	6324·5	0·0002	0·0000	*g*	ASAS-SN (This paper)
2459426·4546	0·0005	1	6334·0	0·0010	0·0008	*V*	Moschner (This paper)
2459426·5979	0·0007	2	6334·5	0·0006	0·0003	*V*	Moschner (This paper)
2459448·8802	0·0008	1	6412·0	0·0014	0·0004	*o*	*ATLAS* (This paper)
2459449·0230	0·0011	2	6412·5	0·0004	−0·0006	*o*	*ATLAS* (This paper)
2459469·4374	0·0005	2	6483·5	0·0021	0·0004	*V*	Moschner (This paper)
2459505·3754	0·0005	2	6608·5	0·0023	−0·0006	*V*	Moschner (This paper)
2459737·8280	0·0012	1	7417·0	0·0090	0·0014	*o*	*ATLAS* (This paper)
2459737·9675	0·0015	2	7417·5	0·0047	−0·0028	*o*	*ATLAS* (This paper)
2459743·0012	0·0007	1	7435·0	0·0071	−0·0004	*g*	ASAS-SN (This paper)
2459743·1449	0·0008	2	7435·5	0·0070	−0·0006	*g*	ASAS-SN (This paper)
2459777·5024	0·0005	1	7555·0	0·0080	0·0004	*V*	Moschner (This paper)
2459777·6467	0·0009	2	7555·5	0·0085	0·0009	*V*	Moschner (This paper)
2459788·4263	0·0005	1	7593·0	0·0067	−0·0009	*V*	Moschner (This paper)
2459788·5698	0·0009	2	7593·5	0·0066	−0·0011	*V*	Moschner (This paper)
2459802·3713	0·0005	2	7641·5	0·0079	0·0003	*V*	Moschner (This paper)
2459802·5141	0·0008	1	7642·0	0·0070	−0·0006	*V*	Moschner (This paper)
2459802·6572	0·0009	2	7642·5	0·0063	−0·0013	*V*	Moschner (This paper)

Survey for Supernovae (ASAS-SN)[19,20] data appear to be unaffected. ASAS-SN observations are typically made in groups of three in the space of $0^{d}{\cdot}003$ (4 minutes), and measurements have been taken from the direct-aperture-photometry pipeline of the individual images. Seasonal composite timings have been derived using a 4-harmonic Fourier fit from 2014–2018 in *V* and

2019–2022 in Sloan *g*. The ASAS-SN *V*-band data provide a valuable extension into the two years preceding the bulk of the time-series data. Data from the *Zwicky Transient Facility* (*ZTF*)[21] are available as individual observations from 2018–2022, in the *zg* and *zr* bands, and although these are unevenly distributed it is possible to derive reliable seasonal minima, again using a 4-harmonic Fourier fit. Data from the *Asteroid Terrestrial-Impact Last Alert System* (*ATLAS*) project[22,23] are typically made in groups of four over about an hour in the cyan and orange bands, so come from one cycle. Observations were downloaded from the *ATLAS* Forced Photometry Server using the simple-aperture-photometry option and seasonal composite timings derived as above for 2016–2022, using both the cyan and the rather more reliable orange-band data. Finally, data were taken from the AllWISE* Multi-epoch Photometry Database[24] which provides less reliable but complementary timings for 2010 in the *W1* and *W2* bands. For all these data sets the times of minimum have been calculated from the original UTC or (M)JD dates as appropriate and the heliocentric corrections calculated using the Terrestrial Time (TT) date, which include the *TAI–UT1* offset of 32·184 seconds and the appropriate number of leap seconds, currently 37. These values have been compared to their BJD_{TDB} equivalents using the routines of Eastman *et al.*[25] and agree within a few seconds, as they should†. All the times of minimum are collected in Table I and the O–C diagram of the residuals with respect to a linear ephemeris is shown in Fig. 2.

The observed times of minimum are fitted to the usual linear form of the ephemeris for the eclipsing binary, plus an offset due to the light-travel-time effect (LTTE) of the companion using the expression given by Irwin[26,27]. The fitting was performed using Markwardt's implementation of the Levenberg–Marquardt algorithm through MPFIT[28]. All the relevant details are given in a previous paper[29].

The initial solutions were calculated for circular and eccentric orbits using the natural weights of the minima as determined from their errors, and these fits generated reduced chi-squared $\chi^2_\nu \approx 2$, which for W UMa systems is not excessive. In this scheme the eccentric solution is preferred as the improvement in χ^2_ν is significant at the 0·5% level according to the F-test, and the eccentricity itself, although small at $e = 0{\cdot}09(2)$, is significant at about 4σ. However, $\omega = 269(3)^\circ$ is suspiciously close to 270°. In these systems large values of χ^2_ν usually point to movement of the eclipses due to chromospheric activity, which also causes the O'Connell effect. Although there is no definitive evidence of this from the light-curve, there has to be the suspicion that it is present. A more realistic estimate of the uncertainties comes from solutions with $\chi^2_\nu \approx 1$ so the weights were limited to the equivalent of an error of $0^{\rm d}{\cdot}0010$ to achieve this value. In this case the eccentric solution is not a significant improvement, so further observations will be required to refine any eccentricity. The solution gives $P_3 = 1413 \pm 9$ d or $3{\cdot}87 \pm 0{\cdot}03$ yr with the light-travel-time $A = 0^{\rm d}{\cdot}00765(14)$. It should be mentioned that because the phase diagram of the orbit is close to being undersampled an alias of this period also fits the data, at some level. However, the alias period, with $P_3 = 492 \pm 1$ d, has $\chi^2_\nu = 8$ and is a poor fit to the data with some runs of points moving counter to the fit, so it is not a viable solution. Derived parameters of the system have been calculated from the well-known expressions for the mass function (see *e.g.*, Hilditch[30]), which gives the minimum mass, $m_3 \sin i$, as a surprisingly large $0{\cdot}95\ M_\odot$ and the corresponding radial-velocity amplitude of the binary as 10 km s^{-1}, so a velocity solution may

*https://wise2.ipac.caltech.edu/docs/release/allwise/expsup/index.html
†On-line utilities https://astroutils.astronomy.osu.edu/time/

TABLE II

Light-travel-time solution

Parameter		*Circular orbit* *Limited weights*	*Eccentric orbit* *Natural weights*	
T_0	=	2457605·41107(17)	2457605·41069(12)	HJD
P_0	=	0·287502755(41)	0·287502782(27)	d
A	=	0·00765(14)	0·00794(9)	d
e	=	0·0 (fixed)	0·086(15)	
ω	=	0·0 (fixed)	269 ± 3	°
T_3	=	2458006 ± 6	2457645 ± 12	HJD
P_3	=	1413 ± 9	1421 ± 6	d
χ^2_v	=	1·109	2·100	
$a_{12} \sin i$	=	1·32(2)	1·37(2)	AU
$f(m)$	=	0·1542	0·1706	$M_\odot$
$m_3 \sin i$	=	0·95	0·99	$M_\odot$
K_{12}	=	10·2	10·5	km s^{-1}

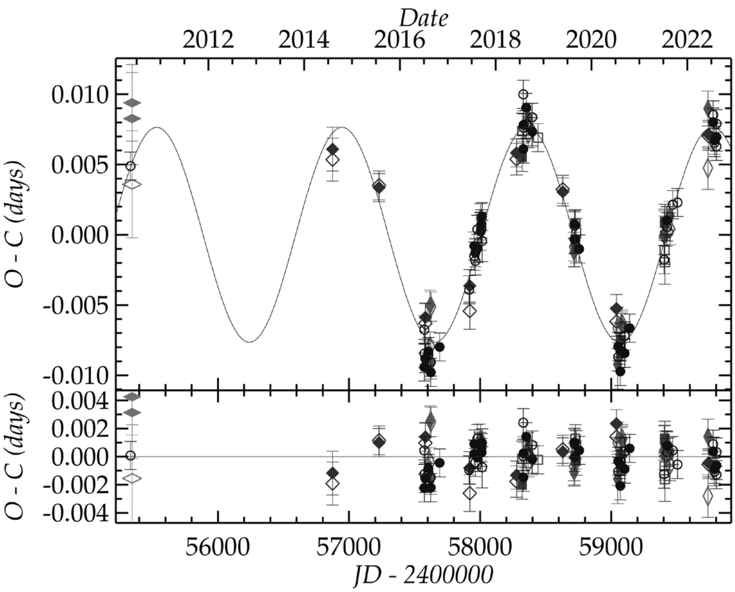

FIG. 2

The O–C diagram of GSC 03937-02349 showing the circular third-body light-travel-time solution. The time-series data are shown as circles, the *WISE* data as flat lozenges, the ASAS-SN data as diamonds, the *ZTF* data as squares, and the *ATLAS* data as tall lozenges. The open symbols are the secondary minima. The residuals from the fit are shown in the lower panel. The errors bars shown are the ones used for the solution and not the measured values listed in Table I.

be possible from high-resolution measurements. The measured and derived parameters are listed in Table II.

As there are no photometric or velocity studies of this system the mass has been estimated from the empirical relationships of Latković *et al.*[3] and Poro *et* *al.*[31] relating period, mass, and temperature. Based on the period these suggest $m_1 = 1{\cdot}0 \pm 0{\cdot}1\ M_\odot$ and $m_2 = 0{\cdot}4 \pm 0{\cdot}1\ M_\odot$. Taking the total mass of the binary as $m_{12} = 1{\cdot}4\ M_\odot$ then the minimum mass of the third body is $m_3 = 0{\cdot}95\ M_\odot$, which is comparable to the mass of the primary of the W UMa binary. The presence of such a massive companion must contribute significantly to the luminosity of the system and may help explain the shallow eclipses.

Relationships between the period and luminosity for short-period W UMa systems suggest that the expected absolute magnitude is about $M_V = 4{\cdot}9$[3,32,33] so it is possible to compare this with the observed value. The distance from Bailer-Jones *et al.*[34] is $d = 870 \pm 130$ parsecs, depending on which measure is taken, and this is consistent with the *Gaia* DR3 parallax. The *Gaia* Collaboration provides additional products through the Apsis processing chain including the reddening, for which it gives $E_{B-V} = 0{\cdot}15$. Rather lower estimates of the reddening of this system are given by the 3D Dust Maps of Green *et al.*[35] $E_{g-r} = 0{\cdot}09 \pm 0{\cdot}03$ and $E_{B-V} = 0{\cdot}09 \pm 0{\cdot}03$ by Lallement *et al.*[36]. The question mark over the *Gaia* reddening is raised partly by the discordance with the other values, but also because the distance given by the Apsis processing, $d = 1378 \pm 10$ parsecs, is inconsistent with the parallax. So, taking $V = 13{\cdot}25$ from the ASAS-SN data and assuming $A_V = 0{\cdot}3$, then the observed mean absolute magnitude of the system is $M_V = 3{\cdot}25$, and some $1^{\rm m}{\cdot}6$ brighter than the anticipated value, meaning the companion would be expected to have $M_V = 3{\cdot}5$. If the *Gaia* Apsis distance and reddening are used then the value becomes a magnitude brighter. If the system is $1^{\rm m}{\cdot}6$ brighter than a standard W UMa binary of the same period then it means that 70% of the luminosity of the system is provided by the companion and the eclipse depths are in reality about $0^{\rm m}{\cdot}5$.

The *Gaia* Apsis processing chain uses the BP/RP spectra to derive additional parameters assuming the source is a single star. One of these is the effective temperature which is a composite of the system but dominated by the companion, and at $T_{\rm eff} = 6000$ K this compares with $T_1 = T_{\rm eff} \sim 5300$ K of the binary from the empirical calibrations[3,32,33]. An independent measure of the effective temperature, in practice the spectral type, has been made by comparing the *Gaia* BP/RP spectra with the Pickles[37] Stellar Flux Library using a minimization scheme that can treat the reddening as a free parameter. The *Gaia* BP/RP spectra were compared with spectra of F5V, F8V, G0V, G2V, and G5V and their luminosity class IV equivalents. The best fit was achieved with the F8V library spectrum, with F8 IV and G0 IV being slightly worse and requiring non-optimal reddening. The fit to the spectrum is shown in Fig. 3. All the other spectra were poor fits and required either excessive or negative reddening to achieve their best fits. From the Rochester calibration (see Pecaut & Mamajek[38]) a star of spectral type F8V has $M_V = 4{\cdot}0$, which is still rather fainter than the $M_V = 3{\cdot}5$ required, but a star in the range F5V–F6V would match the luminosity. The effective temperature of an F8V star is $T_{\rm eff} = 6170$ K, and with a little dilution this is consistent with the *Gaia* value, and supports the notion of a hotter companion.

Very little is known about the GSC 03937-02349 system with any confidence. The binary period, the third body-period, and the light-travel time are reasonably well established, but the minimum mass of the companion is dependent on assumptions made about the mass of the binary. However, within reasonable limits the minimum mass of the third body has to be nearly half the mass of the system. The excess luminosity points to this being a hotter, single star and other W UMa systems are known to have relatively massive companions. VW Cep has a third body of $> 0{\cdot}7\ M_\odot$ and a possible fourth body in a long-period orbit[10], while ER Ori has a third body with a minimum mass of $\sim 0{\cdot}9\ M_\odot$ in a 54-year orbit,

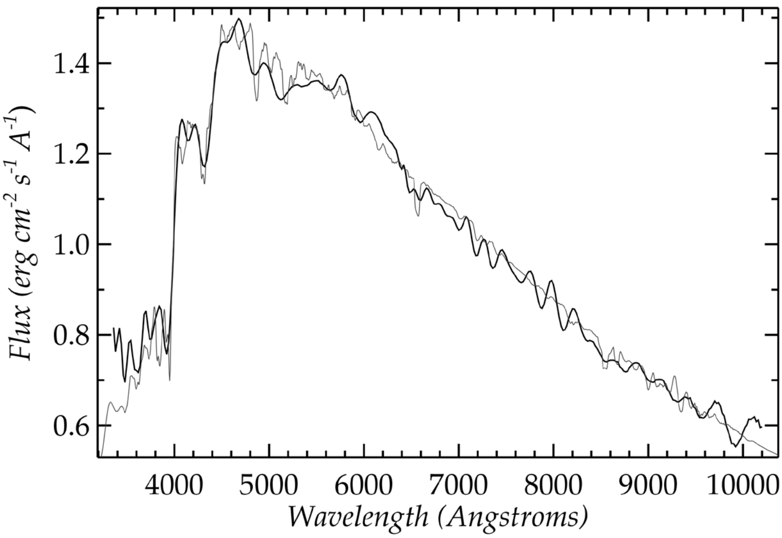

FIG. 3

The *Gaia* BP/RP spectrum (thick line) overlaid with the reddened best fit F8 V library spectrum, assuming $E_{B-V} = 0{\cdot}09$.

but in this case the mass of the binary is about 2 $M_{\odot}$[11]. As mentioned earlier, systems with more massive companions tend to be 2+2 hierarchy quadruple systems, *e.g.*, TZ Boo, V2610 Oph[2], and VW LMi[6], where the two binaries are of comparable mass, but the statistics are poor. GSC 03937-02349 appears to be a potentially important system with a massive companion in a short-period orbit that contributes significantly to the luminosity and is desperately in need of a full photometric model and radial-velocity solution.

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RE-PARAMETERIZATION OF FOUR LIMB-DARKENING LAWS AND THEIR IMPLEMENTATION INTO THE JKTEBOP CODE

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Limb darkening (LD) is typically parameterized using a range of functional 'laws' in models of the light-curves of eclipsing binary and transiting planetary systems. The two-coefficient LD laws all suffer from a strong correlation between their coefficients, preventing a reliable determination of both coefficients from high-quality light-curves. We use numerical simulations to propose re-parameterizations of the quadratic, logarithmic, square-root, and cubic LD laws that show much weaker correlations, and implement them into the JKTEBOP code. We recommend that these re-parameterizations are used whenever both LD coefficients are fitted. Conversely, when fitting for only one coefficient, the standard laws should be used to avoid problems with fixing coefficients at poor values. We find that these choices have little

effect on the other fitted parameters of a light-curve model. We also recommend that the power-2 LD law should be used as default because it provides a good fit to theoretical predictions, and that the quadratic and linear laws should be avoided because they do not.

Introduction

Limb darkening (LD) is a universal phenomenon which modifies the brightness of stars across their disc. LD results in a wavelength-dependent decrease in brightness from the centre of the observed disc to the limb, and in a steeper drop-off closer to the limb compared to near the centre. It arises because sightlines which enter the surface of the star at an angle ('slant viewing geometry') penetrate less deeply into the atmosphere, see cooler plasma than a perpendicular sightline, and so perceive a lower flux.

LD was first noticed in our Sun by Luca Valerio in 1612[1], and was first measured by Pierre Bouguer in 1729[2]. It must be accounted for in any observing project which involves spatially resolving a star, specifically interferometry, eclipsing binaries (EBs), and transiting planetary systems (TEPs). All analysis methods that the author is aware of for EBs and TEPs include a treatment of LD in order to represent properly the characteristics of the object(s) being considered.

In this work we describe the implementation of multiple LD laws into the JKTEBOP⋆ code[3,4] for modelling the light and radial-velocity curves of EBs and TEPs. The novelty of this work lies primarily in the re-parameterization of the coefficients. We begin with a reminder of the different LD laws in use, present the re-parameterizations we adopt, and conclude with advice on using the LD functionality now included in JKTEBOP.

Limb-darkening laws

For the analysis of the light-curves of EBs, LD was implemented in the pioneering Russell–Merrill method[5–9] using the linear law[5,10]:

$$\frac{F(\mu)}{F(1)} = 1 - u_{\mathrm{lin}}\,(1-\mu), \qquad (1)$$

where $F(\mu)$ is the flux at position $\mu = \cos\gamma$ on the stellar disc, γ is the angle between the observer's line of sight and the surface normal, $F(1)$ is the flux at the centre of the disc, and u_{lin} is the linear LD coefficient. The strength of the LD is specified by u_{lin}, which is normally between zero (no limb darkening) and unity (surface flux decreases to zero at the limb).

The linear LD law has been known for over a century to be an inadequate representation of the solar LD[11–14] prompting more sophisticated laws to be proposed: the quadratic LD law (Kopal[15]):

$$\frac{F(\mu)}{F(1)} = 1 - u_{\mathrm{quad}}(1-\mu) - v_{\mathrm{quad}}(1-\mu)^2, \qquad (2)$$

⋆http://www.astro.keele.ac.uk/jkt/codes/jktebop.html the logarithmic law (Klinglesmith & Sobieski[16]):

$$\frac{F(\mu)}{F(1)} = 1 - u_{\log}(1-\mu) - v_{\log}\mu \ln \mu; \quad (3)$$

the square-root law (Díaz-Cordovés & Giménez[17]):

$$\frac{F(\mu)}{F(1)} = 1 - u_{\rm sqrt}(1-\mu) - v_{\rm sqrt}(1-\sqrt{\mu}); \quad (4)$$

the cubic law (van't Veer[18]):

$$\frac{F(\mu)}{F(1)} = 1 - u_{\rm cub}(1-\mu) - v_{\rm cub}(1-\mu)^3; \quad (5)$$

the power-2 law (Hestroffer[19]):

$$\frac{F(\mu)}{F(1)} = 1 - c(1-\mu^{\alpha}); \quad (6)$$

and the four-parameter law proposed by Claret[20]:

$$\frac{F(\mu)}{F(1)} = 1 - \sum_{n=1}^{4} u_{\rm n}(1-\mu^{\rm n/2}). \quad (7)$$

The EBOP code[21,22], on which JKTEBOP is based, used the linear LD law. Díaz-Cordovés & Giménez[17] and Giménez & Díaz-Cordovés[23] modified EBOP to include the quadratic and square-root LD laws. The current author subsequently added these and the logarithmic, cubic, and four-parameter laws into JKTEBOP (versions 12, 15, and 31). We have now added the power-2 law (JKTEBOP version 43) which means that all the laws given above are now implemented in JKTEBOP. The cubic law was included specifically because it was expected that the greater functional difference between the two terms (compared to the quadratic law) would make the two coefficients less correlated; it is shown below that this is indeed the case. It is possible within JKTEBOP to use different LD laws for the two stars, with the exception of the four-parameter law.

Review of published re-parameterizations of the LD laws

Our experience of using the LD laws in JKTEBOP for a wide range of EBs and TEPs is that: the linear law is adequate for most ground-based data but not for light-curves from space missions such as *Kepler*, *CoRoT*, and *TESS*; results from the two-parameter laws are typically in excellent agreement; one should fit for one of the two LD coefficients when possible because theoretical predictions are imperfect; fitting for both LD coefficients in the two-coefficient laws is not recommended because they can be severely correlated. Strong correlations are a particular issue for Markov chain Monte Carlo (MCMC) codes as they cause a long autocorrelation length and thus decrease the number of independent samples in the Markov chains. Support for these statements can be found in correlation plots[24,25] and supplementary material for the *Homogeneous Studies* publications[25–28]. The strong correlations have also been noticed by other researchers, *e.g.,* refs. 29 and 30.

The correlations could be decreased by changing the parameterization of the LD laws, and a range of re-parameterizations have been proposed for the quadratic law. Brown *et al.*[31] fitted for the sum and difference of the LD coefficients:

$$u' = u_{\rm quad} + v_{\rm quad} \tag{8}$$

$$v' = u_{\rm quad} - v_{\rm quad} \tag{9}$$

Holman *et al.*[32] used another:

$$u' = 2\,u_{\rm quad} + v_{\rm quad} \tag{10}$$

$$v' = u_{\rm quad} - 2\,v_{\rm quad} \tag{11}$$

and Pál[30] generalized these to

$$u' = u_{\rm quad} \sin\theta + v_{\rm quad} \cos\theta \tag{12}$$

$$v' = u_{\rm quad} \sin\theta + v_{\rm quad} \cos\theta \tag{13}$$

where θ depends on the properties of the system being studied but is usually between 35° and 40°. Kipping[33] has explored these in detail, and Howarth[34] has discussed the comparison between observed and theoretical LD coefficients.

Maxted[35] proposed a re-parameterization of the power-2 LD law to depend on the coefficients h_1 and h_2 where

$$h_1 = \frac{F(0{\cdot}5)}{F(1)} = 1 - c(1 - 2^{-\alpha}) \tag{14}$$

and

$$h_2 = \frac{F(0{\cdot}5) - F(0)}{F(1)} = c\, 2^{-\alpha} \tag{15}$$

and h_1 and h_2 are only weakly correlated (see also Short *et al.*[36]).

We are not aware of proposed re-parameterizations for any of the other laws, a point also noted by Czismadia[37].

Data for numerical experiments

It is desirable to avoid strong correlations between parameters when fitting the light-curves of EBs and TEPs. We therefore chose to re-parameterize the two-parameter LD laws with coefficients that are less strongly correlated. As several differing options have been published for the quadratic law, and none for any of the other laws (except power-2), we decided to determine our own. The most straightforward way to do this is *via* numerical experiments.

We identified a set of five EBs and TEPs with a variety of properties and for which excellent light-curves exist. The rationale for these choices is that we expected the correlations between LD coefficients to depend on the physical attributes of a given system so needed to include objects with a range of characteristics, and that very high-quality photometry is needed to fit for both LD coefficients in a given system.

The first object we analysed was the EB IT Cas, which was chosen because it shows deep V-shaped eclipses which arise from two very similar stars with an orbital inclination near 90°, and thus should sample the full range of μ values on the stellar discs. For this we used the Simple Aperture Photometry (SAP) from sector 17 of the *Transiting Exoplanet Survey Satellite* (*TESS*) downloaded from the Mikulski Archive for Space Telescopes (MAST*). We used only data with a QUALITY flag of zero, ignored the data errors as they were too small, and rejected all data more than one eclipse duration from the midpoint of an eclipse in order to save computing time. A detailed analysis of this system is in preparation and will be presented in due course as part of the 'Rediscussion of Eclipsing Binaries' project[38].

For our second object we chose WASP-50, a TEP for which an extremely high-quality transit light-curve is available from a ground-based telescope[39]. These data proved to be useful but of insufficient quality to measure reliably two LD

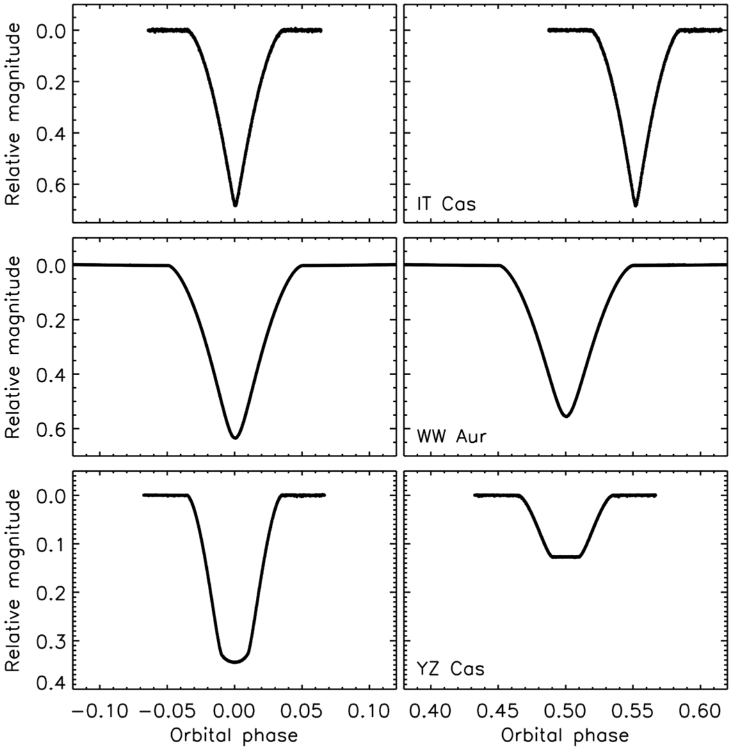

Fig. 1

TESS short-cadence SAP photometry of the three EBs analysed in the current work. The primary eclipses are shown in the left panels and the secondary eclipses in the right panels. The star names are labelled on the panels.

†https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

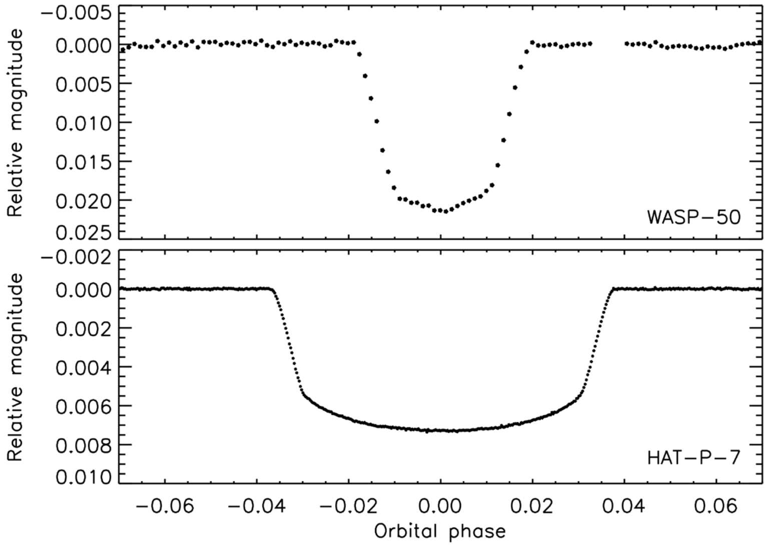

FIG. 2

Light-curves of the two TEPs analysed in the current work from the *New Technology Telescope* (WASP-50) and *Kepler* (HAT-P-7).

coefficients. We therefore chose a third object, the TEP system HAT-P-7[40], for which an extraordinarily good light-curve is available from the *Kepler* satellite[41]. We used the same data as in Southworth[27], which comprise the first 59 transits observed, all in short-cadence mode[42].

We also added a fourth object, the totally-eclipsing binary YZ Cas[43], for which we used the sector-19 data from *TESS*. Finally, after inspection of the preliminary results, we added WW Aur[44] as it shows deep V-shaped eclipses similar to those of IT Cas but has a circular orbit. For WW Aur we used the sector-45 data from *TESS*. For both objects the *TESS* data were prepared in the same way as for IT Cas. The light-curves of the five objects are shown in Figs. 1 and 2. We would have liked to extend this to stars hotter than YZ Cas A but were unable to identify a suitable candidate: all options we explored had either shallow eclipses, large fractional radii, pulsations, or no high-quality light-curve.

The light-curve of each object was modelled using JKTEBOP and a two-parameter LD law, with both LD coefficients fitted. Once a good fit was obtained, we ran a set of 1000 Monte Carlo simulations[45,25], which comprised the generation and then least-squares fit of 1000 synthetic datasets with the same time-stamps as the original data and brightness measurements taken from the original best-fitting model with Gaussian noise applied. This was performed for the quadratic, logarithmic, square-root, and cubic LD laws. We did not consider the linear LD law, because it only has one coefficient so is not affected by correlations between coefficients, or the power-2 law, as the h_1 and h_2 approach was judged to be already satisfactory. Conversely, the four-parameter law exhibits such strong correlations between its coefficients that we considered it to be a lost cause so made no attempt to re-parameterize it.

New re-parameterizations

We first assessed the linear Pearson correlation between the two LD coefficients in each Monte Carlo simulation, using the correlate function in IDL*. The results are given in Table I and support several conclusions. First, the correlations between u and v are in general horrendous. Second, we notice that the correlations are at their worst when the data are of the highest quality. Third, the coefficients of the square-root law exhibit almost perfect correlations so should never be fitted together. Fourth, the coefficients of the cubic LD law have the lowest correlations, supporting the expectation mentioned above.

TABLE I

Linear Pearson correlation coefficients between the u and v coefficients of the two-parameter LD laws, assessed using Monte Carlo simulations as implemented in JKTEBOP, for each of the five objects included in the numerical experimentation.

Object	*quadratic law*	*logarithmic law*	*square-root law*	*cubic law*
IT Cas	−0·982	+0·998	−0·999	−0·952
WASP-50	−0·951	+0·994	−0·996	−0·605
HAT-P-7	−0·992	+0·992	−0·999	−0·973
YZ Cas	−0·978	+0·987	−0·999	−0·914
WW Aur	−0·995	+0·997	−0·999	−0·985

We next sought alternative parameterizations that would reduce these correlations. We chose a functional form that is similar to that of Pál[30] but simpler:

$$u' = u + xv \tag{16}$$

$$v' = u - xv \tag{17}$$

where the quantity x can be chosen to minimize the correlation between u' and v' for each LD law. The implementation of this in JKTEBOP was done by modifying the input and output sections but converting the LD to the original parameterizations when calculating a model data point. This meant that we needed only the inverse transforms, which can easily be shown to be:

$$u = \frac{u' + v'}{2} \tag{18}$$

$$v = \frac{u' - v'}{2x} \tag{19}$$

independently of the LD law.

*http://www.harrisgeospatial.com/SoftwareTechnology/IDL.aspx

TABLE II

Values of x which minimize the correlation between u′ and v′, for each LD law and each object studied.

Object	*quadratic law*	*logarithmic law*	*square-root law*	*cubic law*
IT Cas	0·44	0·75	0·57	0·19
WASP-50	0·59	0·57	0·51	0·29
HAT-P-7	0·62	0·60	0·62	0·39
YZ Cas	0·63	0·64	0·60	0·33
WW Aur	0·58	0·62	0·62	0·35
Adopted value	0·6	0·6	0·6	0·3

We then determined the value of x, for each LD law and for each object, that minimized the correlation between u' and v'. This was done by manual iteration and was restricted to two significant figures in x both for convenience and to avoid unnecessary precision. These values are given in Table II and show that the best value of x depends on both the object and the LD law, as expected. The results are highly consistent, with the exception of IT Cas for which significantly different x values are found in some cases. A plausible explanation for this is that IT Cas is the only object with an eccentric orbit, and the inclusion of $e \sin \omega$ as a fitted parameter has modified the correlations between the LD coefficients. However, an exploratory Monte Carlo simulation with $e \sin \omega$ fixed showed the same result so this supposition was not confirmed.

Given this relatively good consistency in x, we chose suitable values for implementation in JKTEBOP for general use: 0·3 for the cubic law and 0·6 for the other three laws. For clarity, here are the revised versions of the LD laws we propose:

$$u'_{\rm quad} = u_{\rm quad} + 0{\cdot}6\, v_{\rm quad} \qquad (20)$$

$$v'_{\rm quad} = u_{\rm quad} - 0{\cdot}6\, v_{\rm quad} \qquad (21)$$

for the quadratic law,

$$u'_{\rm log} = u_{\rm log} + 0{\cdot}6\, v_{\rm log} \qquad (22)$$

$$v'_{\rm log} = u_{\rm log} - 0{\cdot}6\, v_{\rm log} \qquad (23)$$

for the logarithmic law,

$$u'_{\rm sqrt} = u_{\rm sqrt} + 0{\cdot}6\, v_{\rm sqrt} \qquad (24)$$

$$v'_{\rm sqrt} = u_{\rm sqrt} - 0{\cdot}6\, v_{\rm sqrt} \qquad (25)$$

for the square-root law, and

$$u'_{\rm cub} = u_{\rm cub} + 0{\cdot}3\, v_{\rm cub} \qquad (26)$$

$$v'_{\rm cub} = u_{\rm cub} - 0{\cdot}3\, v_{\rm cub} \qquad (27)$$

for the cubic law.

We assessed the correlation between u' and v' for each of these laws and for each of the five objects to gauge the improvement brought by the revised laws. These are given in Table III and show a clear improvement in all cases. There are nevertheless still some strong correlations, particularly for the logarithmic and square-root laws. We recommend that these laws are not used when attempting to

Table III

Linear Pearson correlation coefficients between u′ and v′ in our new LD law parameterizations, calculated for each of the five objects included in the numerical experimentation using Monte Carlo simulations.

Object	*quadratic law*	*logarithmic law*	*square-root law*	*cubic law*
IT Cas	−0·860	+0·969	−0·888	−0·842
WASP-50	−0·034	−0·375	−0·890	−0·028
HAT-P-7	+0·206	−0·022	+0·704	−0·222
YZ Cas	−0·207	+0·383	−0·064	−0·745
WW Aur	−0·363	+0·374	−0·711	−0·688

fit both coefficients of a two-parameter LD law. As an example, in Figs. 3 and 4 we show scatter plots of the Monte Carlo simulation output for WW Aur, for the LD laws in their original form, for the lowest correlation for this object, and for the recommended re-parameterizations.

Several published re-parameterizations of the quadratic LD law[31,32,30] were quoted above. We checked these against each of our five objects (allowing for values between 35° and 40° for the functional form proposed by Pál[30]) and found that they all yielded significantly stronger correlations than the re-parameterizations proposed in the current work. Finally, we did not attempt to compare the coefficients to theory in order to avoid ‘mission creep’.

Testing the new LD laws

Now we had re-parameterizations of the LD laws and implemented them into JKTEBOP, we proceeded to test the code and assess the effect of the revised LD laws. To limit the computational load of this work we analysed only one object, WW Aur, and fitted only the data near eclipse in the first half of the light-curve from *TESS* sector 45. Best fits and 1000 Monte Carlo simulations were performed for the linear LD law, for all two-parameter laws in their original form, for the re-parameterizations presented here, and for the h_1 and h_2 approach for the power-2 law. Initial or fixed LD coefficients were set to values for the Cousins R passband from Claret & Hauschildt[46], with the exception of the power-2 law for which we used the *TESS*-passband predictions from Claret & Southworth[47]. We also ran two fits using the four-parameter LD law: one with coefficient u_2 fitted and one with u_2 and u_4 fitted. The values of the fixed coefficients were taken from Claret[48].

We report only the most relevant results from this work: the r.m.s. scatter around the best fit, the fractional radii (r_A and r_B), and the orbital inclination (i). These are given in Table IV with error bars assessed using the Monte Carlo simulations. The error bars are not true uncertainties, as Monte Carlo simulations are only one of the tools typically deployed in our error analyses[49], and are almost certainly too small[50]. Extensive comparisons between the results from different LD laws can also be found in the supplementary material to our *Homogeneous Studies* papers[25–28] for 94 TEPs.

Based on experience, Table IV, and the *Homogeneous Studies* supplementary material, we draw the following conclusions. First, the linear LD law is too simplistic and gives slightly different results to those from all other LD laws. It should not be used except for convenience in cases where the data quality is low. Second, the re-parameterized laws give results that are consistent with the original laws. Third, fitting for both LD coefficients yielded comparable results

TABLE IV

Selected results from fitting the TESS light-curve of WW Aur with one or two LD coefficients fitted, for all possible versions of the one- and two-parameter laws. N_{cof} is the number of LD coefficients fitted. The bracketed quantities indicate uncertainties in the final digit of the preceding values.

LD approach	N_{cof}	*rms (mmag)*	r_A	r_B	i (°)
Linear law	1	0·350	0·15958 (4)	0·15121 (4)	87·550 (2)
Quadratic law	1	0·343	0·15973 (4)	0·15148 (4)	87·497 (2)
Logarithmic law	1	0·352	0·15957 (4)	0·15118 (4)	87·555 (2)
Square-root law	1	0·341	0·15973 (4)	0·15140 (4)	87·508 (2)
Cubic law	1	0·341	0·15973 (4)	0·15138 (4)	87·510 (2)
Power-2 law	1	0·341	0·15971 (4)	0·15138 (4)	87·512 (2)
Quadratic re-par.	1	0·342	0·15972 (4)	0·15146 (4)	87·501 (2)
Logarithmic re-par.	1	0·647	0·16019 (7)	0·15254 (7)	87·300 (4)
Square-root re-par.	1	0·341	0·15973 (4)	0·15140 (4)	87·508 (2)
Cubic re-par.	1	0·348	0·15960 (4)	0·15124 (4)	87·543 (2)
Power-2 (h_1 and h_2)	1	0·342	0·15970 (4)	0·15136 (4)	87·517 (2)
Quadratic law	2	0·342	0·15969 (4)	0·15141 (4)	87·510 (3)
Logarithmic law	2	0·341	0·15972 (4)	0·15141 (4)	87·508 (3)
Square-root law	2	0·341	0·15973 (4)	0·15140 (4)	87·508 (3)
Cubic law	2	0·341	0·15974 (4)	0·15139 (4)	87·507 (3)
Power-2 law	2	0·341	0·15974 (4)	0·15141 (4)	87·507 (3)
Quadratic re-par.	2	0·342	0·15969 (4)	0·15141 (5)	87·510 (3)
Logarithmic re-par.	2	0·341	0·15972 (4)	0·15141 (4)	87·508 (3)
Square-root re-par.	2	0·341	0·15973 (4)	0·15140 (5)	87·508 (3)
Cubic re-par.	2	0·341	0·15973 (4)	0·15140 (4)	87·508 (3)
Power-2 (h_1 and h_2)	2	0·341	0·15974 (4)	0·15141 (5)	87·507 (3)
Four-parameter	1	0·341	0·15970 (4)	0·15136 (4)	87·517 (2)
Four-parameter	2	0·341	0·15972 (4)	0·15139 (4)	87·509 (3)

to fitting for one coefficient in the case of WW Aur, for which the data are of extremely high quality. Fourth, the anomalously poor solution in Table IV for the re-parameterized logarithmic law suggests that the re-parameterized laws risk giving bad results if only one LD coefficient is fitted and the other coefficient is fixed at a bad value.

Summary

A profusion of LD laws have been proposed, many of which have two coefficients. All of these suffer from strong correlations between the two coefficients which hinders the modelling process of observed light-curves when both coefficients are fitted parameters. We have proposed a re-parameterization of the quadratic, logarithmic, square-root, and cubic laws and performed numerical simulations to calibrate the re-parameterizations. This was done considering three EBs and two TEPs with a variety of light-curve shapes.

We give the following recommendations:

1. Light-curves of low quality can be modelled using either the linear law for simplicity, or one of the two-parameter laws with one or both coefficients fixed.

2. Light-curves of medium quality should be modelled using one of the standard two-parameter laws, with one coefficient fitted and one fixed.

3. Light-curves of high quality should be modelled including two LD coefficients as fitted parameters. In this case the re-parameterized laws should be used to avoid the strong correlations found with the standard two-parameter laws. This is particularly important for sampling algorithms such as Markov chain Monte Carlo (MCMC), to avoid long autocorrelation lengths in the Markov chains.

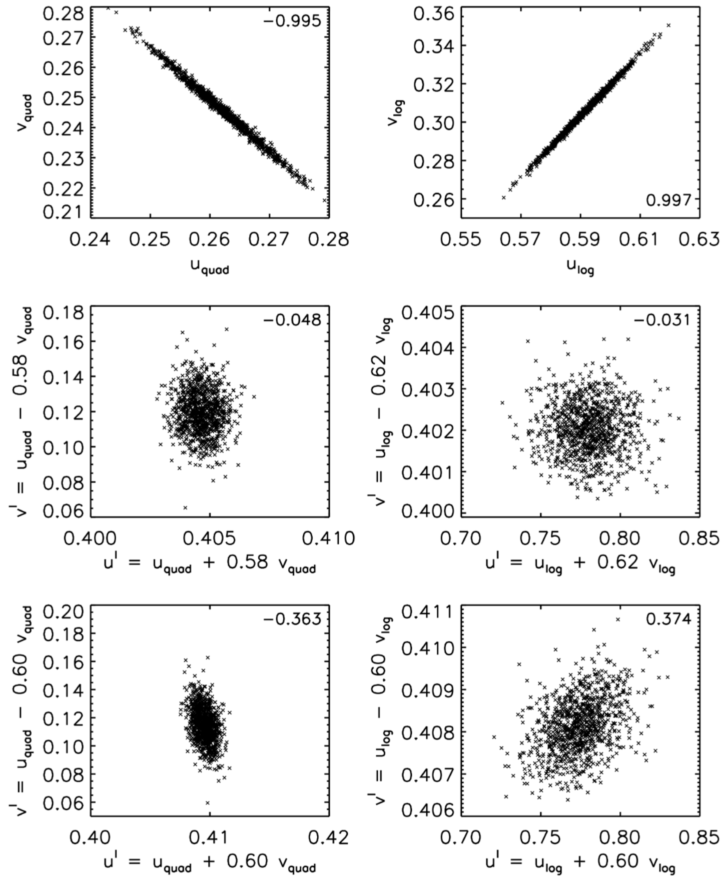

FIG. 3

Scatter plots of the LD coefficients for the quadratic and logarithmic laws obtained from fitting the light-curve of WW Aur and then performing 1000 Monte Carlo simulations. The correlation coefficient is printed in each panel.

4. If you are unsure whether a light-curve is of low, medium, or high quality, you should try two or all three options and decide which is best based on the values of and uncertainties in the fitted LD coefficients (and other system parameters).

5. The linear LD law should be avoided when performing any detailed analysis.

6. The quadratic LD law should be avoided as it does not match theoretical LD predictions well[47,51].

7. The power-2 LD law should be adopted as the default law because it *does* match theoretical LD predictions well[35,47,52].

8. The four two-coefficient LD laws give highly consistent results when treated in the same way, so the choice between them is not important.

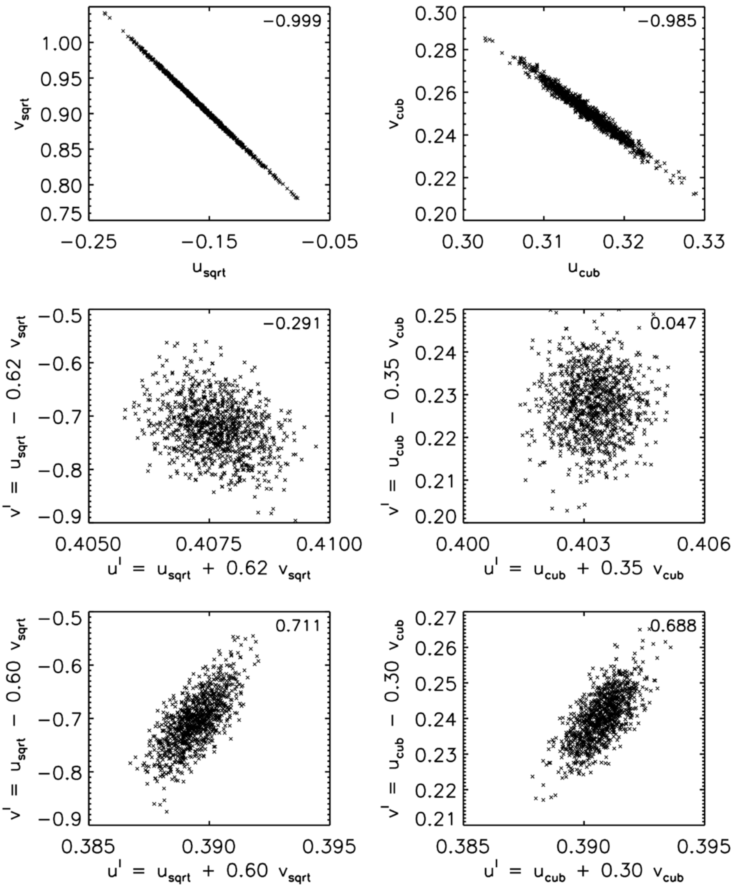

FIG. 4

As Fig. 3 but for the square-root and cubic LD laws.

9. The best re-parameterization of a given LD law varies slightly between light-curves. If this is an issue, or if you want to avoid parameter correlations as much as possible, you should use principal component analysis (PCA) to orthogonalize the model parameters in the course of obtaining a least-squares solution to a given light-curve.

All LD laws and re-parameterizations have been implemented in version 43 of the JKTEBOP code, which is freely available for download from the author's website. The choice of which LD function to adopt is left to the user.

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REVIEWS

Venus, by William Sheehan & Sanjay Shridhar Limaye (Reaktion), 2022. Pp. 256, 23 × 18 cm. Price £25 (hardbound; ISBN 978 1 78914 585 4).

This is the ninth title in Reaktion's well-received Kosmos series, and it easily lives up to the standard of the previous books. Limaye has investigated the atmosphere of Venus with the *Pioneer Venus*, *Venus Express*, and *Akatsuki* missions, while Sheehan brings his expertise to the volume as a writer and historian, having already penned or co-authored three of the previous titles in the series.

We start off with an historical approach, and the wanderings of Venus in the sky are the main topic of Chapter 1. We are then into the realm of telescopic discoveries over the next three chapters. Some unusual illustrations are included throughout the book, such as a portrait of Bianchini and even one of a globe made from his observations. As the authors say, the early observations were not necessarily wrong, but they were incorrectly interpreted, and this trend continued right up to the 1950s, with one camp favouring an atmospheric rotation period equal to the Earth's day and the other preferring one as long as 225 days. Both were wrong. Indeed, I have seen series of hourly drawings published by two early-20th-Century observers, one based in America and the other in England, which were said to show the rotation of the planet. But it was rotating in the wrong direction!

Transits of Venus at least gave a reliable estimate of the Astronomical Unit, and the authors describe and illustrate the exciting and perilous expeditions that went out to observe them. The cause of the infamous 'black drop' is correctly attributed to the effect of inadequate resolution exacerbated by bad seeing. It was good to read more background information about the early ultraviolet photographic work of Frank Ross, and of Charles Boyer's later role in determining the atmosphere's four-day UV rotation period, described here accurately and in detail.

One point that might have been mentioned is the Juvisy Observatory's 1910 July report of the emergence from occultation by Venus of a bright star: one that allowed a first good estimate of the great depth of the planet's atmosphere. The Ashen Light, now known from the *Parker Solar Probe* to be a real phenomenon, is too easily dismissed as illusory in Chapter 4.

Radar and spacecraft appear in Chapter 6 onward. There is a nice history of rocketry, and the role of carbon dioxide and methane in global warming upon the Earth and Venus is discussed. (After 35 years of a career in education

I was eventually forced to raise the '0·03% CO_2' in Earth's atmosphere that I had been teaching to '0·04%'. An apparently small but profoundly shocking change.) The ground-based radar measurement of the slow surface rotation, coupled with the high carbon-dioxide level, implied that Venus must be a very hot world indeed. Confirmation would soon be forthcoming from *Veneras 4–6* and *Mariner 5* in 1967–69. The authors describe the gradual accumulation of more detailed knowledge about the surface and atmosphere as a result of later space missions. There is a description of atmospheric dynamics and how the Y-shaped features imaged in the UV evolve. There is also a nice discussion of what we would still like to know about the atmosphere. The authors do not mention the mysterious and remarkably large north–south cloud 'discontinuity' observed in the far infrared by *Akatsuki* in 2015.

Chapter 8 discusses the surface of Venus, with many images and charts. Throughout this chapter and the rest of the book the quantity and quality of the illustrations is impressively high. The remaining chapters discuss possible life on or above Venus, and the practical observation of the planet. Numerical data about the planet and lists of space missions are nicely presented in Appendices. There are very extensive references.

In summary, *Venus* is a very well-written book that is easy to read, highly informative, full of inspiring insights, and appropriately amusing at times. It will appeal to anyone wishing for an up-to-date introduction to Earth's twin. — RICHARD MCKIM.

Imaging Our Solar System. The Evolution of Space Mission Cameras and Instruments, by Bernard Henin (Springer), 2021. Pp. 271, 24 × 16·5 cm. Price £24·99 (paperback; ISBN 978 3 030 90498 2).

This book traces the historical development of imaging instruments launched into space and includes some of the most iconic images taken of our Solar System. It describes the early beginnings involving photography from a helium balloon at an altitude of 22 km in 1935, and covers all the many subsequent achievements including the remarkable fly-by and imaging of the trans-Neptunian object, Arrokoth, in 2019 that attained a resolution of 33 m per pixel whilst some 6·6 billion km from Earth.

To tell this story, the author has collated technical information on the various instruments lofted into space from many disparate sources and assembled it in one readable volume comprising three sections: Part I, 'First Lights', covers space probes through to *Voyager* that were based on vidicon-type image scanning or single photosensors; Part II, 'Dawn of the Digital Era', describes when CCD cameras were flown into space starting with the armada of craft sent to intercept Comet Halley in 1986; and Part III, 'The New Golden Era', begins with missions launched in 2000 through to 2021 when a plethora of successful space firsts were achieved.

A preface outlines the theory and mechanics behind space-borne imaging followed by a history recounting the successes and failures of the Space Race that ultimately led to the Moon and planets beyond. These first chapters read very well and engender some of the excitement arising from the development of new technologies, and which led to many new discoveries in planetary science. Together with the later chapters, the book provides a comprehensive reference source about every space mission to visit planets and other small Solar System bodies but, the potential reader should note, it specifically excludes all solar probes.

The text is well illustrated with 54 black-and-white and 59 colour images, and has three appendices tabulating dates, details of missions, *etc.*, plus a bibliography and index. As part of the Springer Praxis Books series, it is also available as an ebook. — Richard Miles.

Soviets in Space, by Colin Burgess (Reaktion), 2022. Pp. 174, 24 × 16·5 cm. Price £25 (hardbound; ISBN 978 1 78914 632 5).

At the present time, it would not seem unreasonable to regard Russia as a second-rate space power, but for much of the 20th Century the Soviet Union ran a close second to the United States in the so-called space race. For those too young to remember those days, this fairly short book by space historian Colin Burgess provides a useful summary of the achievements and failures, triumphs and tragedies, associated with the Soviet and Russian human-spaceflight programmes. All of the key events of the Soviet space endeavour are described, starting with the ground-breaking theoretical work of pioneers such as Konstantin Tsiolkovsky, and the inspirational leadership of Sergei Korolev, the anonymous chief designer of so many of the first Soviet rockets and spacecraft.

The basic groundwork for sending people into orbit was achieved after the Second World War, with the help of captured German scientists and hardware. This eventually led to the launch of the world's first artificial satellite, *Sputnik*, in 1957, followed by the use of mongrel dogs to test the ability of living creatures to survive the stresses of launch, weightlessness, and a fiery re-entry.

Continuing in chronological order, the book devotes two chapters to the first cosmonauts, most notably Yuri Gagarin, who risked their lives to beat the United States into orbit and returned to Earth by ejecting from their spacecraft and then parachuting to the ground. Other chapters describe the multi-crewed Voskhod missions that were a stopgap effort to compete with the more sophisticated US Gemini programme, the failure of the Soviets to compete with NASA's Apollo lunar programme, and the fatally flawed flights of two Soyuz spacecraft that killed four crew. There is also a chapter devoted to the brief period of détente which saw the Soviets and Americans participate in a joint flight in 1975.

The book concludes with an overview of the *Mir* space station, a multi-modular design that has inspired the Chinese station which is currently under construction in orbit, and a brief look at the present state of the Russian space programme, with its focus on shuttling crews to and from the *International Space Station*.

This well-written book offers an ideal introduction to the Soviet/Russian human-spaceflight programme, which has now passed its 65th anniversary. It may well inspire readers to seek more detailed descriptions and analysis in other sources. — Peter Bond.

Astronomy Photographer of the Year (Collection 11), compiled by the Royal Observatory Greenwich (Collins), 2022. Pp. 182, 26·5 × 27 cm. Price £25 (hardbound; ISBN 978 0 00 853262 8).

Astronomers are doubly fortunate: some results of their science can be presented in striking images and astronomy has long attracted talented amateurs, many of whom have turned to astrophotography. Latterly they have been joined by photographers inspired by astronomical phenomena for artistic imagery. Since 2009, a highly appropriate showcase for all such work has been provided by the annual Astronomy Photographer of the Year competition and exhibition organized by the Royal Museums Greenwich. The present volume presents the 138 entries shortlisted in the 2022 competition, including winners in each of the eight categories: 'Skyscapes', 'Our Sun', 'Galaxies', 'Our Moon', 'Aurorae', 'Planets, Comets and Asteroids', 'People and Space', and 'Stars and Nebulae'. In addition, there are entries for the Sir Patrick Moore Prize for the best newcomer, the Annie Maunder prize for image innovation (*i.e.*, artistic processing of publicly available images from professional facilities), and the young competition.

Each photograph in the book is accompanied by an account, in greater or less detail, of the instrumentation used, exposure times, and sometimes the post-production software and circumstances of the photography. There is a wide variety of instrumentation, including cameras, home-built and commercial telescopes, and the remote use of telescopes at distant, good sites operated for those willing to pay a modest fee. For example, many of the images in the book come from observations with one or another of the telescopes at Observatorio El Sauce in Chile, located in Valle Rio Hurtado about 20 km from *Gemini South*. Many photographs were taken through narrow-band filters, producing striking results, and one photographer in the 'young' competition, Zezhen Zhou, made the point next to his image of NGC 6979 that one could use these for successful astrophotography even in his light-polluted city. We're told of meticulous planning, waiting, often in the cold, to catch the moment, or stacking up huge numbers of images for the deep-sky objects — total integration times often exceed 30 hours. Comments from the judges are added to some of the captions, together with background astronomical information by members of the Museum staff. The astronomer in me would have liked an indication of scale but I accept that this is not essential to appreciate the images. Similarly, that the curvature of the Milky Way in some of the panoramic photographs favours composition over scientific fidelity.

The images themselves are stunning — I'd be happy to have some of them on my walls — and the reproduction generally good, but I noticed a few small artefacts, light irregular rings, on images of the Sombrero Galaxy (p. 51) and Jupiter (p. 94). I cannot imagine that the photographers would have missed them and assume they come from the printing. This is supported by the absence of any artefact on a downloaded version of one of the images. More serious is a flaw in the book design: most of the prize-winning photographs are printed across two pages, losing some of the image in the gutter. This does no favours to the photographers or the readers. I am aware that the proportions of some of the photographs present problems for the square book pages but don't think that I'm alone in being willing to accept less magnification in order to see all of each image. — Peredur Williams.

Dust in the Galactic Environment, 3rd Edition, by D. C. B. Whittet (IoP Publishing), 2022. Pp. 293, 26 × 18·5 cm. Price £120/$190 (hardbound; ISBN 978 0 7503 3273 6).

Astronomers and astrophysicists who have an interest in interstellar dust are sure to have to hand a copy of Whittet's *Dust in the Galactic Environment*, either the first edition (1992) or the second edition (2003). These books have been splendid and reliable guides to the nature and properties of Galactic dust. But as Whittet notes in his Preface "this new edition is in large part a different book". Indeed, even rather standard material has been largely re-written and extended; it appears in five chapters under the broad heading of 'The Observed

Properties of Dust'. These chapters include those on extinction and polarization along with three more chapters on infrared absorption features, continuum and line emission, and elemental depletions. There are chapters on the circumstellar origins of dust and the role of dust in the evolution of the interstellar medium during star and planet formation. The final chapter summarizes what we know about dust, and — more importantly — what we don't know. This chapter should be a delight for those seeking new problems to address.

The extensively re-written third edition has of course been necessary because of the enormous number of important results arising from observations made using facilities such as the *Herschel Space Observatory*, *Planck Space Observatory*, and *Spitzer Space Telescope*. Whittet himself has been a principal investigator of observing programmes with the *Hubble Space Telescope*, the *Spitzer Space Telescope*, and the *Infrared Space Observatory*. It is now clear that — far from being merely an irritating fog preventing a clear view of the stars — dust has crucial active roles in astrochemistry, in interstellar evolution, and probably in astrobiology. These roles are also being explored by studies of stardust in meteorites, and by laboratory experiments on dust analogues.

The book is beautifully produced with extensive use of colour images and diagrams. Each chapter includes extensive references to recent literature. The level of the text is certainly appropriate for advanced undergraduates and for postgraduates; established researchers will also benefit from this book. I have two niggles, more to do with IoP Publishing than the author. Why is there no index? This seems a significant omission. Why do the page headings throughout the book merely repeat the book's title? It would be more helpful to show the chapter and section titles. Perhaps these points might be addressed in the fourth edition! In summary, however, this is an excellent, comprehensive, and essentially new book on Galactic dust, and is thoroughly recommended. — David A. Williams.

Extragalactic Astrophysics, 2nd Edition, by James R. Webb (IoP Publishing), 2022. Pp. 157, 26 × 18·5 cm. Price £75 (hardbound; ISBN 978 0 7503 3549 2).

This seems a strange book for the IoP to produce (as part of their ebooks series) if they have the British market in mind. It is aimed, according to its Preface, at "a graduate level class in a physics department where student's [*sic*] available credit hours for astrophysics classes are limited". I'm not sure any corresponding courses exist in British universities. Leaving that aside, what about the content? Basically, it is a (fairly random) selection of topics in areas which could be taught in at least half a dozen separate undergraduate courses during a UK astrophysics or physics-with-astrophysics degree. For instance, the 'Introduction' covers stellar structure and evolution, with a couple of pages on galaxies at the end. However, the only topics considered in any depth are polytropes and radiative transfer through a stellar atmosphere. The equations of stellar structure are essentially just quoted and stellar evolution gets four lines (giant stars are not mentioned). We are also given in passing "the famous *Voight-Russell theorem*", which evidently isn't famous enough for the author to spell Vogt correctly. Chapter 2, 'The Milky Way Galaxy' follows the same course, with the only detailed analyses being those of stellar number counts and of Oort's Constants. The contents of the ISM are covered in half a page. 'External galaxies' tells the reader quite a lot about epicyclic motion and gamma-ray bursts. 'General relativity and cosmology' is standard cosmological fare, though with somewhat mangled discussions of "Obler's" paradox and of curvature

("K < 0, a→ c-K the Universe is hyperbolic"). On the other hand, the 'Active galaxies, quasars and supermassive black holes' chapter, which is the longest and most detailed (it is the author's research area), contains several lengthy and complex derivations. Mistakes of various sorts are fairly widespread, ranging from the daft ("the sidereal period … squared is equal to the orbital period cubed"), through the outdated ("visible matter only makes up about 30%, dark matter and dark energy make up the remaining 70%"), to the plain incorrect (mistakes in the derivations of some equations). The typesetting is also poor in places. Finally, the author really shouldn't have bothered with the oddments of history. Claude Messier, anyone? (Charles' long-lost brother perhaps?) Or Martin Slipher? (Apparently he worked on Cepheids, which Vesto didn't.) And J. L. E. Dreyer may have been in Ireland, but he wasn't the 4th Earl of Rosse. In summary, I don't know why the publishers bothered and any prospective buyer probably shouldn't. — Steve Phillipps.

Golden Years of Australian Radio Astronomy, by Wayne Orchiston, Peter Robertson & Woodruff T. Sullivan III (Springer), 2021. Pp. 268, 24 × 16 cm. Price £44·99 (hardbound; ISBN 978 3 319 91841 9).

Here is a book to be welcomed warmly by the current generation of Australian radio astronomers, as it details much of what went on — not so much what as by whom — during those crucially formative years from the end of WW II to the conclusion of the century. Attractively produced by Springer and richly illustrated (it describes itself as an "illustrated history") with nearly 300 photos from a central archive, its strong feature is the sequence of page-long thumbnail sketches of nearly 50 of the people who visualized, planned, constructed, and operated the numerous instruments and work-places that materialized from their plans and efforts.

The Radiophysics Laboratory (RPL), with its headquarters in Sydney, operated as a hub for some 20 linked outposts, but those decades were also still the heyday of the individual who chose to develop ideas alone (until very limited funding ran out). Many of the famous pioneers in radio astronomy either started at, passed through, or settled at, Australian observatories during the period covered by this book. A mere three examples include the native Australian C. W. Allen (who trained there before becoming a research and teaching professor in the UK), the arch-individualist, American-born Grote Reber (who found Tasmania an accepting country to dwell for much of his life as he investigated low-frequency set-ups), while Australian-born Ruby Payne-Scott (the world's first woman radio astronomer) spent her active scientific years in or near Australia's central labs (RPL) or its daughter outposts. These were also the days of communication by letter, furnishing a rich archive of documents and photos to detail the many experiments that were carried out by the players on the various scenes. The yield is a variegated book concerning a great many individuals bent on solving the technical and scientific (cosmological) puzzles that frustrated such pioneering spirits worldwide.

These were early days for all radio astronomers, in the northern hemisphere as well as in the Antipodes. Projects tended to be experimental rather than routine, and the general shortage of experience was a common handicap. Competition for supremacy inevitably triggered some rivalry between the two hemispheres, and this book does rather harp on what was later shown to be a mistake on the part of the British. Expressions of rivalry again raise their heads in the final chapter, where a glimpse into radio astronomy's future faces the unpalatable decision that the site of the *Square Kilometre Array* (*SKA*) is not to be that of radio astronomy's avowed (Australian) 'founding fathers' but is to be shared with South Africa, thereby robbing the Australians of their assumed dominance. The pain and annoyance thus incurred, its depth reflected in the large volume of space dedicated to that one matter, reverberates to the end. But that is not surprising, since (by definition) this book only observes the Australian angle.

Golden Years is the result of a prodigious amount of scholarship. All the same, radio astronomers who were personally part of, or can recall, that period and some of the many anecdotes and events reported will appreciate it most. Outsiders may find it too cluttered with information and detail to be so attractive. It lacks a main theme; like a scrapbook that includes all the family photos, its aim seems to be to regurgitate everything that could be considered relevant to the topic of radio astronomy in Australia during the period in question, resulting in an overabundance of subsidiary photos and tidbits of conversations at the expense of an account that reflects the true growth in progress and understanding. Its authors would therefore have produced a more acceptable book had they decided at the outset whether they were describing progress in technology, modelling, and understanding and how the Australian efforts were (or perhaps were not always) significant sources of those achievements — or whether the book was really meant to be purely a collection of stories and people. — Elizabeth Griffin.

"Well, Doc, You're In." Freeman Dyson's Journey Through the Universe, edited by David Kaiser (MIT Press), 2022. Pp. 295, 23·5 × 16 cm. Price $29·95 (about £27) (hardbound; ISBN 978 0 262 04734 0).

Freeman Dyson was an extraordinary man, in the full sense of that adjective. He was endlessly curious and interested in everything, and his research career reflected that. Born in 1923 in Berkshire, he was brought up in Winchester, where his father, George, was musical director at Winchester College and a violinist. Dyson took up the violin as a child, but although he played it well, he "played mathematics even better", to quote one of the authors of this fascinating collection of articles. He even discovered infinite series for himself before he was four years old.

His upper-middle-class parents left him to be brought up by the domestic staff, but the house was full of books, and he devoured these, especially popular-science books. These included, at the age of seven, Eddington's description of relativity using a light-cone diagram. He also read science fiction and even wrote his own science-fiction story.

Aged eight, he went to a local prep school, where he escaped bullying by taking refuge in the library. Gaining a scholarship to Winchester College, he made close friends with Christopher Longuet-Higgins and his brother Michael, and also James Lighthill, who referred to themselves as the "gang of four". This gang also made full use of the College library, working their way at the age of fourteen through the three volumes of Jordan's *Cour d'analyse* (in French) and the equally daunting *Principia Mathematica* by Whitehead and Russell, both way beyond the school syllabus.

All this information comes from the first article in the book. To cover Dyson's wide-ranging interests, the editor (himself a physicist, at MIT) has assembled a set of ten authors (including himself and two of Dyson's children), with equally wide-ranging backgrounds, from theoretical physics to science policy, science journalism, chemistry, and the history of science. After school, Dyson spent a strange two years as an undergraduate in an almost empty wartime Cambridge, taught by such eminences as Dirac, Eddington, Hardy, Littlewood, and Besicovich (who taught him Russian as well as mathematics). It was at this time that he started what proved to be a lifelong correspondence with his parents; most of these letters survive, and have been a valuable source for this book. In 1943, Dyson found himself seconded to the RAF to work on operational research, then a very new subject, and used his mathematical skills to great effect in Bomber Command.

After the war, Dyson returned to Cambridge, finished his mathematics degree, and started on a PhD. He soon made the transition from pure mathematics to theoretical physics, moving to Cornell in 1947 on a Commonwealth Fellowship to study with Hans Bethe. At that time, the theory of quantum electrodynamics (QED) was bedevilled by the problem of infinities that seemed to appear whenever physicists tried to calculate the mass corrections arising from interactions with virtual particles. Bethe had recently found an approximate way of losing the infinities, but it was not at all rigorous. He set his new colleague the task of improving the calculation, including relativistic effects. In a mere three months, Dyson transformed the theory of QED and submitted it for publication. A second year, now at the Institute of Advanced Study (IAS) in Princeton, introduced him to Feynman and his famous diagrams, which Dyson was able to use to transform QED into a self-consistent theory. The resulting publication sealed his reputation and made him widely known in the physics community. It was at the 1949 January meeting of the American Physical Society in New York (p. 85), where a speaker kept referring to "the beautiful theory of Feynman-Dyson", that Feynman made his comment "Well, Doc, you're in." that gives the book its title.

At the end of his Fellowship, he returned to the UK to hold a Royal Society Fellowship at Birmingham. Soon after this, Feynman moved to CalTech, and Dyson was invited back to Cornell to replace him. Despite not having finished his PhD (he never did), he was by far the best candidate for this permanent position. He was 26. Two years later, he was offered a permanent research position at IAS, where he was based for the rest of his long life.

He loved to dabble in all sorts of different problems, describing himself (p. 105) as a frog "who live(s) in the mud and … delight(s) in the details of particular objects". He contrasted this with birds who "fly high in the air and survey broad vistas of mathematics", saying that many of his best friends were birds. He switched academic fields many times, working in pure mathematics (*e.g.*, properties of modular forms and applications of random matrices), climate change, arms control, extraterrestrial life, the origin of life, space travel, and others. Although always contributing a new idea that was often orthogonal to the existing consensus, he never dominated any one field. During his time working on space travel, he penned this insightful distinction between physics and engineering: "A good physicist is a person with original ideas. A good engineer is a person who makes a design that works with as few original ideas as possible".

Despite all these scientific (and some political) activities, he was also a family man who loved children, played often with his own, and was loved by them in return. He and his second wife, Imme Jung, had four daughters, the eldest of whom, Esther, contributes the final chapter in the book. She says that Dyson interacted with many people who were not scientists (*e.g.*, waiters, airline pilots) and with both his children's friends and his friends' children.

All the chapters in the book are well written, and each illuminates a different facet of Dyson's career, giving a rounded picture of this clever, attractive, and modest man. It's a great read and I recommend it wholeheartedly. — ROBERT CONNON SMITH.

When Galaxies Were Born: The Quest for Cosmic Dawn, by Richard S. Ellis (Princeton University Press), 2022. Pp. 253, 24·5 × 17 cm. Price £25 (hardbound; ISBN 978 0 691 21130 5).

I had been looking forward to this book and wasn't disappointed. It's an enjoyable romp through the last fifty years or so of important parts of extragalactic astronomy, seamlessly integrated with the story of the technology which made that possible and the life of the author, one of the most important players in the field. Unless one knows all three topics really well, one will certainly learn something from this book, which has the added advantages that it is well written and exudes the author's enthusiasm for his work and for life in general (some more details, especially those of a more personal nature, can be found in the transcript of a Caltech oral-history interview[1]).

Ellis, born into a Welsh-speaking family in North Wales, like many picked up a fascination for astronomy as a child from library books, soon progressing to a home-made telescope. Unlike most, he made it into a very successful career, working with the largest telescopes in the world and being invited onto the television programme of the author of the book which had initially inspired him, (later Sir) Patrick Moore. While it is difficult to have a more successful career than that of Ellis, at the same time not only scientific decisions have shaped his career, but also the goal of a sensible work–life balance, no doubt helped by arriving as an undergraduate at UCL at the end of the Swinging Sixties. Concentrating on astronomy rather than his rock group, The Omegas, Ellis enjoyed a range of high-level positions in astronomy, including that of the Plumian Professor of Astronomy and Experimental Philosophy at Cambridge and Director of Palomar Observatory at Caltech, before, after a short stint at ESO, returning to UCL.

The nine main chapters (there is also an epilogue, concentrating on *JWST*) are organized mainly around the principal telescopes: the Palomar 200-inch, the *AAT*, the *WHT* on La Palma, the *HST*, the *Keck* telescopes, and modern ESO telescopes. Ellis's work is concerned mainly with observational cosmology, in particular the origin and evolution of galaxies and the quest to observe the earliest galaxies (reflected in the subtitle), which has necessitated using increasingly powerful instruments to observe galaxies at higher and higher redshifts, including using amplification *via* gravitational lensing to observe objects which, unlensed, would be too faint for even the largest telescopes. Although including figures from journal papers and so on, the description of the science should be understandable even to those not familiar with the topic. Many will have encountered various aspects of it before, but it is interesting to hear it told from one point of view by one of the major players, who also helped develop many of the necessary instruments; personal details and the politics of science make the story even more fascinating.

There are 18 black-and-white figures scattered throughout the text (diagrams, pictures of people or landscapes) and 87 colour plates (most consisting of more than one image) in two groups. The few footnotes usually provide references. There is no bibliography as such, but five pages of small-print illustration credits include references for figures from papers and so on. Those interested in even more details can start with Ellis's *Annual Review* on 'Faint Blue Galaxies'[2] (which, along with his time(s) at Oxford — including his PhD work, after which he briefly considered non-academic careers such as advertising executive — comes across as one of the few things not completely enjoyable). The book ends with a seven-page small-print index.

This is a wonderful book. I'm sure that most readers would get something out of it and many would get much out of it; the same goes for those interested in astronomy and its recent history who are not readers of this *Magazine*, from amateurs to professionals. — PHILLIP HELBIG.

References

(1) https://oralhistories.library.caltech.edu/234/
(2) R. S. Ellis, *ARAA*, **35**, 389, 1997.

First Dawn. From the Big Bang to Our Future in Space, by Roberto Battiston (MIT Press), 2022. Pp. 199, 23·5 × 15·5 cm. Price $32·95 (about £27) (hardbound; ISBN 978 0 262 04721 0).

This book, as its subtitle indicates, is a description of our current understanding of the creation and subsequent development of the Universe. It is written for the layman rather than the professional astronomer, and covers the historical background, present beliefs, and what is now happening to extend our cosmological comprehension.

I have been reading books on this subject since 1939 (*Mr Tompkins in Wonderland*) and I found this one as enjoyable as any. The author is an eminent Italian physicist whose special field is elementary particles, but whose interest in and appetite for all aspects of cosmology is conspicuous, as is his wish to share it with the reader. In one sense his compact and comprehensive information is disappointing: the broad background of cosmography has not changed greatly since George Gamov's *Creation of the Universe* published in 1952, and although our ever-increasing observational ability has brought in many exciting astronomical discoveries (exoplanets, pulsars, gravitational waves) the widest expansion of knowledge has been the particle explosion and the field of quantum mechanics, which has tended to lead to increasingly baffling situations rather than clarity. Dark energy, dark matter, the scarcity of antimatter, wave–particle duality, and other enigmas all add to the bewilderment of the layman. It is, however, implicit in the book that these problems are seen as motivational challenges by those wrestling with them.

The book opens with the rather unscientific Einstein quotation "What really interests me is whether God had any choice in the creation of the world." This has the merit of reminding the reader that Einstein himself was never entirely comfortable with all aspects of quantum mechanics, particularly nonlocality, and also makes the point that cosmogony includes theology and philosophy. It is easy, and I suppose inevitable, that professional cosmic researchers tend to disregard the vast amount of human thought applied over the centuries to the origin concepts put forward by different religions and the tenacity with which they are held despite their scientific improbability.

But to return to the book itself, the chapters are unusually short, there are no illustrations or diagrams, and there is virtually no mathematics. To me in this context these are all virtues — the author has a great deal to convey, covering what we do and what we don't know and what has been and is being done to improve the situation, and the text therefore calls for and merits serious application, which is aided by the comparative brevity of the chapters and the absence of the potential distraction of pictures. The lack of mathematical involvement is also beneficial, to me at least, because numbers are not a natural entity like exoplanets or protons, and although they are essential to our exploitation of matter they excite so much emotive enthusiasm, particularly in the truly gifted mathematician, that the scientific integrity of their reality may be imperilled. It is relevant that the author mentions Einstein's comment "I have trouble with Dirac".

I found 'ten infernal minutes', the chapter dealing specifically with the Big Bang moment, particularly interesting and well presented, with the uncertainty principle applicable to the ultimate pre-Bang small dimension giving rise to quantum fluctuations with balanced positive and negative energy aggregated to zero but capable of expanding to become the Universe. Alan Guth's "ultimate free lunch" is quoted, before the author goes on to describe the subsequent and more easily comprehensible establishment of the four fundamental forces and then of particles. To what extent this vacuum-energy concept is now generally accepted I do not know, but it is certainly more interesting than simply calling the episode a singularity.

Towards the end of the book there is a lot of information about modern space and particle exploration, the effect of politics and international co-operation, and the increasing involvement of wealthy individuals — Elon Musk, SpaceX, Virgin Galactic, Burt Rutan's aircraft — all of which leaves the reader with an impression of worldwide activity which may lead to major discoveries and even the much heralded Grand Unified Theory of Everything. But will it? The chief merit of this book is to make the reader think about all aspects of cosmic knowledge, and as indicated above our basic ideas have not changed much since 1952 but the puzzles revealed by our on-going discoveries have multiplied. Towards the end of the book the author mentions the growth of artificial intelligence and its success (particularly in playing chess) but proffers the final cheerful conclusion that the human mind has the potential to continue to spearhead the research that may ultimately hit the gold; and Hilaire Belloc's definition of genius — "the ability to think in a very large number of categories" — is perhaps a pointer in this regard.

A few more mundane comments in conclusion are that the Foreword to the book is unnecessary and that a glossary would as always be a boon to the reader. Also the author refers in a speed-development context to the "legendary Marquise" car of *c.*1900. I know of no automobile of that name and I think he means the Mercedes developed in 1901 from the Cannstatt Daimler of 1899. But these minor criticisms, and a little prolixity here and there, do not mar a book which I found comprehensive within its remit, conspicuously demonstrative of its author's expert knowledge and enthusiasm, and thought provoking to an extent that might make it of interest to the professional astronomer as well as the layman. — Colin Cooke.

Fundamental Ideas in Cosmology: Scientific, Philosophical and Sociological Critical Perspectives, by Martín López-Corredoira (IoP Publishing), 2022. Pp. 244, 26 × 18·5 cm. Price £99/$120 (hardbound; ISBN 978 0 7503 3773 1).

This book is something of a curate's egg, but well done. The subtitle gives an idea about the contents: it is mainly about the pillars of the standard model of cosmology (expansion, dark matter, dark energy, the CMB, big-bang nucleosynthesis, structure formation) and alternative explanations for various aspects. Film critic Roger Ebert once said "It's not what a movie is about, it's how it is about it", meaning that in reviewing a film one needs to distinguish the topic of the film from the expertise of the director; it is possible to like either, both, or neither. I don't agree with many of the points (some in contradiction with others) presented by the author, but that is not a problem as one point of the book is to present a diverse range of views. I don't always agree with his own views (which he sometimes mentions), but that is not a problem because another point is to encourage discussion and debate.* Both are needed. However, I sometimes disagree with the way various arguments are presented, which is my main complaint about the book. Also, as with a liberal or conservative newspaper, sometimes the problem is not with the facts themselves nor with their presentation but rather with their selection.

The good part is that the book provides not only a good summary of the standard model but also of alternatives to it, from the sublime to the ridiculous. (A minor gripe is that that spectrum might be a bit too broad.) With a total of 969 references (including titles), most of which are to articles from major journals in the field and most of which are relatively recent†, both the standard model and its alternatives are well documented for those who want to explore the details; with such a broad scope, the book can be only an introduction to the science it covers, which it does well in the first seven chapters. It is rare that someone is so well informed both about standard cosmology and alternative theories. There are good summaries of the inflationary paradigm and the history of dark matter, mentioning details often glossed over in similar books. The last three chapters examine sociological and cultural factors and the author's own stance.

López-Corredoira is on the staff of the Instituto de Astrofisica de Canarias (IAC) on Tenerife and has a large number of publications on a wide range of topics, mainly on cosmology and extragalactic astronomy but also on the history, philosophy, and sociology of science. He describes himself as "a philosopher-scientist, within a realist, materialist and sceptical tradition of continental European philosophy, but steadfastly eschewing from postmodern approaches", thus a man after my own heart. Nevertheless, although we both support the general goal of scepticism and debate, we disagree to some extent on what should be considered reasonable and some of the explanations for why cosmology has taken the course it has. While it is certainly the case that few alternative theories are taken seriously by most of the community, and while it is probably true that it is more difficult to get funding for research on such theories, which does mean that they are less well developed than the standard model, I don't think that is the only, or even the main, reason why they have not been as successful. In most cases, they just aren't as good and couldn't be improved even with considerable effort. While in the book the standard model is approached sceptically, alternatives to it aren't subjected to the same criticism (while the author argues that the reverse is what happens in practice, which is probably true in a minority of cases). Apart from distinguishing too little between well-founded (but wrong) theories by professional scientists and ideas based on misunderstandings by amateurs, some of the alternative explanations have been convincingly rebutted, but such rebuttals (as well as observational data which rule out such explanations) are often not mentioned. That gives the impression that the predominance of the standard model is due more to sociological factors

*A couple of months ago, I was part of a discussion on the decline of debate in cosmology. We agreed that there was probably more debate in the past and that there should be more debate now, but also that it should be civil: debate about the issues as opposed to attacking others.

†Such details are conveniently provided in the appendix.

than is actually the case. (That has also changed with time; I would agree that when the Einstein–de Sitter model was the standard model, the primary reasons for it were not scientific.) Whatever one thinks of Kragh's argument[1] that Nobel Prizes awarded for work in cosmology imply that cosmology is a respectable science, it is at best inconsistent to criticize Kragh's argument while at the same time always mentioning Alfvén's Nobel Prize (which was not for cosmology) in connection with his unorthodox ideas about cosmology.

I don't think that cynicism helps the debate, *e.g.*, comparing the age of the Universe of 13·787 ± 0·020 Gyr with the calculation of the age of the Earth by Bishop Ussher, as if the former is just as doomed to become obsolete as the latter. Some claims stated as fact are simply wrong, such as that dark energy was invented to explain the magnitude–redshift relation for Type Ia supernovae. First, no sort of dark energy other than the cosmological constant is needed to explain such data, and second it was present already in the first paper on relativistic cosmology[2] and, though some set it to zero for simplicity, was often used as a free parameter in cosmology in the following decades[3]. Citing references (*e.g.*, ref. 4*) for wrong claims, such as that 'concordance cosmology' implies only that there is one set of parameters which fits all observations but not that there is an independent confirmation of any single parameter, or that non-detection of dark-matter particles at some arbitrary time (and ignoring the fact that dark matter might be in some other form) should rule out ΛCDM, doesn't help. In such cases, I hear an axe being ground. Other claims are probably due to confusion shared by many, such as a conflation of the ideas of fine-tuning and the Anthropic Principle.

Like other books in the 'IOP ebooks' series, using a chapter–page-numbering scheme, rather than consecutive page numbers, is distracting and doesn't seem to serve any purpose. The book is well structured but chapter (even pages) and section (odd) running heads would be useful; instead, all running heads are just the title of the book. There are a few diagrams, most in colour, throughout the text and notes are footnotes rather than endnotes. There is no index, but one would be useful in a book such as this, which would also benefit from proof-reading/editing, especially by a native speaker of English. References are at the end of each chapter.

I can't unconditionally recommend the book, mainly because, similar to López-Corredoira's criticism of Merritt[6], it sometimes tries to be an objective judge and proponent of one side at the same time. While I would always hesitate to recommend a book I see as fundamentally wrong, something which is obviously an opinion piece promoting one side of an argument is easier to deal with and can be used for at least getting an overview of a certain side in a debate. This book is neither. On the other hand, there is much information here which would require many sources and much work to duplicate and the book could prove a valuable resource as a jumping-off point for those interested in learning about debates in modern cosmology, but readers will have to judge for themselves which debates are actually worth worrying about. — Phillip Helbig.

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(1) H. Kragh, *Phys. Phil.*, **008**, 14, 2007.
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*Interestingly, later in the book the author shares my criticism[5] of Merritt[6] trying to be simultaneously judge and jury.

(3) S. M. Carroll, W. H. Press & E. L. Turner, *ARAA*, **30**, 499, 1992.
(4) D. Merritt, *Stud. Hist. Phil. Mod. Phys.*, **57**, 41, 2017.
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From the Library

The New Background of Science, by Sir James Jeans (The Macmillan Company, New York; Cambridge University Press), 1922. Pp. 301, 20 × 13·5 cm. Price not given; no ISBN number. Acquired by Clinton B. Ford in 1933 September; purchased at auction from the American Association of Variable Star Observers.

James Hopwood Jeans (who became Sir in 1928) may ring a couple of bells, first as the eponym of the Jeans length and mass and co-calculator of the Rayleigh–Jeans (long-wavelength) portion of a black-body spectrum. Faithful readers of these pages (both of you) will also recall that a biography of him, written/edited by his son, Christopher, appeared recently and was reviewed in these pages (**141**, 262, 2021). Seven of his (at least 12) books were intended for "the educated public" rather than for fellow scientists.

This one came somewhere near the middle, and the author explains the timing by saying: "After undergoing a succession of kaleidoscopic changes, theoretical physics appears to have attained a state of comparative quiescence." Those kaleidoscopic changes were Special and General Relativity and the Bohr atom, later leading to the new quantum mechanics of Heisenberg, Schrödinger, and Dirac. Most of the chapters are devoted to explanations of the contents of these new portions of physics, Jeans apologizing that he cannot do this without "using a few mathematical symbols and formulae".

Jeans then explains that he has tried to present the new physics (typically in contrast with 19th-Century ideas) "in such a way that every reader can form his own judgment as to its philosophical implications". But throughout, the reader is given only two choices, between two 'conjectures', those of the idealist and the realist, and those of mentalism and materialism. Only the last of these four is likely to be too much misunderstood — Jeans did not mean valuing only the piling up of material things, but rather thinking that material things exist outside the minds of the valuers. Idealism then is not expecting the world to be or get better than it is but supposing that only minds and their ideas exist. Thus the equations of the physicist do not relate one real entity to another, but only our ideas of something to our ideas about something else.

A contemporary philosopher, L. Susan Stebbing (1885–1943) devoted a whole book, *Philosophy and the Physicists* (Methuen, 1937), to berating both Jeans and Sir Arthur Stanley Eddington for their "nebulous philosophy". She was harder on Jeans than on Eddington, but both were censured for their desire to be entertaining in their writings and for appealing to emotion at "the level of a revivalist preacher". If my copy should surface again, Prof. Stebbing (the first woman to hold such a position in England) might also feature in 'From the Library'. But meanwhile, why might one have a go at reading Jeans? Perhaps because very few since have tried so hard to clarify the relationship between GR and QM and our naïve ideas about the world. — Virginia Trimble.

THESIS ABSTRACTS

Cosmology from the CMB and Lyman-α Forest

By Roger de Belsunce

In this thesis, we study challenges arising in cosmological-data analysis using data from the cosmic microwave background (CMB), remnant radiation from the Big Bang, and the Lyman-α forest, absorption features in spectra of distant quasars. A six-parameter standard model of cosmology, the ΛCDM model, can explain to great accuracy how the Universe evolved from a hot, dense state to the web of galaxies that we observe today. However, it leaves fundamental questions about the nature of dark matter and dark energy unanswered, despite these making up 95% of the observable Universe. The advent of large cosmological surveys present a unique opportunity to infer some of the fundamental laws governing our Universe. Extracting the full potential of this data set is an on-going challenge because of its size and highly non-linear nature.

In the first part, we present an end-to-end analysis pipeline for large-angular-scale CMB data. We present novel foreground-removal techniques, improved modelling of the noise and systematics in the data, and develop and extensively test novel likelihood-approximations. The accurate representation of likelihoods including systematics is challenging: exact likelihoods are either unknown or intractable. We present methods that show how to make reliable inference for the optical depth to reionization (τ) or primordial gravitational waves, parametrized by the tensor-to-scalar ratio (r), from large-angular scale CMB data from the *Planck* satellite. The methods presented range from exact pixel-based likelihoods, maximum-entropy-based semi-analytic likelihood-approximations, to simulation-based, so-called likelihood-free, approaches to constrain cosmological parameters. We exhaust current CMB data sets with the developed methods and discuss their potential for next-generation surveys of the CMB.

The upcoming *Dark Energy Spectroscopic Instrument* (*DESI*) survey will measure spectra for tens of millions of galaxies and quasars, constructing a three-dimensional map spanning the nearby Universe to 11 billion light years. The Lyman-α forest consists of a series of absorption lines that map the distribution of neutral hydrogen in the intergalactic medium. This allows us to probe the matter distribution of the Universe at intermediate redshifts $2 \leq z \leq 5$. In the second part of this thesis, we present and develop new continuum-fitting methods to extract the un-absorbed flux of a quasar spectrum. We will discuss methods to constrain cosmology using this rich new data set. — *University of Cambridge; accepted 2022 September.*

The Origin and Evolution of Warm Exozodiacal Dust

By Jessica K. Rigley

Many stars show excess mid-infrared emission which is attributed to warm dust in the habitable zone of the star, known as exozodiacal dust, or exozodi for short. Such dust will be a source of noise and confusion when attempting to detect and characterize Earth-like planets. Therefore, an understanding of exozodiacal dust is crucial to our search for habitable planets and life. In this thesis, I present theoretical models for the origin and evolution of warm exozodiacal dust. Observations find a strong correlation between the presence of warm habitable-zone dust and cold belts of planetesimals similar to the Solar System's Kuiper Belt. Given this correlation and the short lifetime of dust grains close to the star, it is probable that exozodiacal dust originates further out in the planetary system and is transported inwards.

One possible transport mechanism is Poynting–Robertson (P–R) drag, which causes dust grains to lose angular momentum and spiral in towards the star. Initially, I develop an analytical model for the interplay of P–R drag and catastrophic collisions in a debris disc which predicts the levels of exozodiacal dust dragged into the habitable zone of a star from a cold outer belt. I show that detectable outer belts should produce exozodi levels tens of times higher than our zodiacal cloud *via* P–R drag, but these levels are insufficient to explain a large fraction of exozodiacal dust detections. In-depth application of the model to the exozodi of β Leo suggests the presence of an additional, warm, asteroid belt to explain the radial profile of habitable-zone dust.

An alternative mechanism is inward scattering of comets, which spontaneously fragment to produce dust. I then develop a numerical model for the zodiacal dust produced by spontaneous fragmentation of Jupiter-family comets in the Solar System. This is able to produce enough dust to sustain the zodiacal cloud, and give the correct radial and size distribution of dust. I show that cometary input to the zodiacal cloud should be highly stochastic, depending on the sizes and dynamical lifetimes of comets scattered in. The comet-fragmentation model is then extended to be applicable to other planetary systems, taking into account the different dynamical effects. This model will show how much dust comets produce and its evolution after being released from a comet to give exozodi radial profiles.

Finally, I summarize the work in this thesis, and discuss the future outlook and my planned projects for furthering our understanding of exozodiacal dust. — *University of Cambridge; accepted 2022 June.*

OBITUARY

Maarten Schmidt (*1929–2022*)

Maarten Schmidt passed away on Saturday, September 17, 2022. He is famous for his identification of the redshift of the 'Quasi-Stellar Object' 3C 273 in 1963. This demonstrated that quasars, as sources like this became known, were very distant and, consequently, more luminous than their galaxy hosts. Quasars are now associated with supermassive black holes in the nuclei of galaxies and understanding their nature transformed our understanding of galaxies, high-energy astrophysics, and cosmology. Understanding how they evolved over cosmic time became one of Maarten Schmidt's long-term interests. Another highlight of his long and distinguished research career was the discovery of an important relationship between the gas density in a galaxy disc and the rate of star formation.

Maarten Schmidt was born in 1929 in Groningen and joined Caltech as a faculty member in 1959 where he took on several positions of scientific responsibility including leading Hale Observatories and being President of the American Astronomical Society. His accomplishments were acknowledged in many ways including the award of the Royal Astronomical Society Gold Medal in 1980 and the first Kavli Prize in astrophysics, which he shared with Donald Lynden-Bell in 2008. Many of his colleagues, including me, benefitted greatly from Maarten Schmidt's wise, measured, and always friendly advice and opinions. — ROGER BLANDFORD.

Here and There

ONLY IF VIEWED FROM THE SIDE

e, the eccentricity, defining the shape ... of the ellipse, where $e = 0$ is a circle and $e = 1$ is a line. — *Neptune: From Grand Discovery to a World Revealed* (Springer), 2021, p.38.