Eclipsing Disc Systems as a Probe Into Binary Stellar and Planetary Evolution

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At various stages of their evolution, stars and planets are seen enshrouded by flattened discs of gas and dust. In the case of stars, these discs can be formed from their natal protostellar material, via mass transfer from a binary companion, or from a decretion disc around a super-critically rotating star. In the case of planets, these discs may arise during planetary formation or from the collisions or tidal disruption of satellites. When these discs are observed transiting the face of their host star with time-series photometry, the exact structure of the eclipsing disc can be inferred. In this way, the simple geometry of these discs provides an avenue for modelling the complex physical processes that invoke their formation. This review focuses on the observational characteristics of these disc-eclipsing binaries (be they circumstellar discs or transiting planetary rings), and what these transits can reveal about binary stellar and planetary evolution. With the recent success of wide-field photometric surveys, including upcoming missions such as the Legacy Survey of Space and Time (LSST), we expect that orders of magnitude more disc-eclipsing systems will be observed.

I. INTRODUCTION

Discs are ubiquitous throughout astrophysics, found everywhere from planetary ring systems (Charnoz et al., 2018) to protostellar discs (Tobin & Sheehan, 2024) to active galactic nuclei (Padovani et al., 2017) and galaxies as a whole (Graham, 2013). Stars are born embedded within discs as a result of angular momentum conservation following the collapse of molecular clouds, with planets often forming in turn from these natal discs (Andrews, 2020). For close binary star systems in particular, circumstellar and accretion discs are expected to form at various times as the component stars evolve and transfer mass, whether on or after the main sequence, as remnants, or some combination thereof. Similarly, discs are present throughout various stages of some planets' lifetimes – such as Saturn's, and even the ancient Earth's (Tomkins et al., 2024) – both during their formation and in the form of rings sculpted by exo-moons and their collisions or tidal breakup.

The mostly widely used method of studying stars and planets alike is in time-series photometry, where the apparent brightness of an object or system over time is called a 'light curve'. Photometry is observationally cheap and can be done with a series of short exposures viewing up to thousands of targets simultaneously. In surveying the sky this way, we can see in real-time how the stars change either due to intrinsic or extrinsic factors. In the former case, stellar variability such as flares or pulsation modes are common. In the latter case, one possible phenomenon is the transit of an astrophysical companion (another star or planet) over the face of the star which reveals itself in a sharp dip in observed brightness.

The observational characteristics of light curve eclipses, such as the dip depth and breadth, provide strong constraints on the type of eclipsing object. On account of their size, occulting stars produce a correspondingly broader and deeper transit than a planet would on the same orbit. Over the course of an orbital period, secondary eclipses are also observed where the primary star occludes the companion resulting in another dip that is shallower. When combining information of the primary and secondary eclipses together, some degeneracies or unknowns in the object parameters can be broken. In particular, spectra taken during each eclipse can be compared to that out of eclipse to determine the chemical signature and temperature of each component.

With the operation of several wide field survey programs, such as the *Kepler* Space Telescope (Borucki et al., 2010), Zwicky Transient Facility (ZTF; Bellm et al., 2019) and the Transiting Exoplanet Survey Satellite (TESS; Ricker et al., 2015) among others, thousands of companion objects have been discovered using light curves. Considering that the orientation of the companion orbital plane needs to be almost exactly along the line-of-sight, relatively few companions out of the total population are detected.

Recently, there have been an increasing number of observed eclipses which cannot be simply explained by a transiting planet or star. These eclipses display especially broad and deep profiles and have been well modelled as transiting dusty discs or planetary ring systems. Given that eclipsing binaries/transiting planets are only observed in chance alignments, the fact that only a handful of these extended eclipses have been discovered establishes them as truly rare and unique phenomena.

Transiting disc and ring systems are invaluable to

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our understanding of stellar and planetary evolution. Much in the same way that eclipsing binary stars break model degeneracies in the parameters of stars and their orbits (Southworth, 2012), eclipsing circumstellar discs uniquely reveal the structure and chemistry of accretion processes and dust formation. Similarly, eclipsing planetary ring systems inform us of the dynamical history of planets and moons, and are increasingly important in understanding our solar system in comparison to the observed population of exoplanets. Eclipsing discs and rings are the ideal probe into these physics as they are conceptually easy to model; to first order these structures are opaque, simple geometric discs that do not require complex hydrodynamical modelling to simulate. As a result, statistical inference of model parameters in these systems is possible.

In this review we focus on the physics of periodic transiting objects associated with discs and rings. The reason for this is the underlying physics of these systems can be uniquely constrained by repeated eclipse observations, and several objects are understood so well for this reason only. The so called 'dipper' stars share some observational similarities with the systems discussed in this work (e.g. Ansdell et al., 2016), although their light curves are aperiodic and chaotic, and are beyond the scope of this work which focuses on systems where simple geometries can be used to gain physical insight.

We begin this review by discussing the circumstellar and circumbinary disc eclipsing systems in Section II. The history of the prototypical and by far most well-studied disc-eclipser ε Aurigae is reviewed in Section II.A. The observational and physical characteristics of discs in evolved systems is reviewed in Section II.B, with a divide between short and long period systems on the basis of their disparate physical interpretations. In Section II.C we discuss the unique physics of observed discs in pre-main-sequence systems with a particular focus on the more commonly seen circumbinary discs. We share the observed exoring eclipsing systems in Section III, and finally provide an outlook on the field of observing astrophysical discs with photometry in Section IV.

II. DISC ECLIPSING SYSTEMS

There have been several disc eclipsing binary systems observed to date. The underlying nature of these systems is not homogeneous, with a categorical divide between post- and pre-main-sequence stages of stellar evolution resulting in disc formation. Historically the post-main-sequence systems have been the most rigorously studied on account of their brightness making a comparatively larger population visible, although discoveries of pre-main-sequence disc eclipsers have been increasingly common in recent years.

In this Section we review the broad physical and observational characteristics of the circumstellar disc eclipsing systems. One particular system stands out among these as by far the most well studied and whose nature was mysterious for over 150 years, and so we begin by discussing the prototype disc eclipser ε Aurigae.

A. ε Aurigae

As the prototype disc eclipsing system, ε Aurigae (ε Aur) is a binary system consisting of a F0Ia and B5V star (Hoard et al., 2010). The first indication of variability in ε Aur was observed in 1821 by German astronomer Johann Heinrich Fritsch, when the system displayed a ~ 0.8 magnitude dip in brightness, indicative of a binary eclipse. While many eclipsing binary systems are known and well understood, ε Aur stands out in particular due to its especially prolonged eclipse profile. Most eclipsing binaries have transit periods of order days or less, though the periodic occultations of ε Aur last $\sim$ 700 days and repeat every 27.1 years corresponding to the systems orbital period (Stencel et al., 2011).

The first physically motivated interpretation of this eclipse profile was made by Kuiper et al. (1937), suggesting that the transiter is a semi-transparent and large star. Prior to the next observed transit, Kopal (1954) proposed a ring of material around the secondary component to explain the eclipse profile; this idea was first modelled by Huang (1965) with a geometrically and optically thick disc in orbit of the F0 giant. Naturally, an extended and optically thick disc of material obscures the bright star for longer than even a giant star might. This model was refined by Wilson (1971) to an inclined and thick disc of material surrounding the binary stellar companion being responsible for the transit. This inclined thin disc model featured a cavity around the central star within the disc (as would be expected based on models of accretion and dust discs) motivated by the presence of a mid-eclipse increase in brightness of the system (see the middle panel of Figure 1, approx day 55400) which is not reproduced from a simple edge-on disc model. This model was favoured for decades, with various refinements to match new incoming photometric and spectroscopic data. Notably, Carroll et al. (1991) suggested that the disc may be thin with a variable opacity throughout the disc profile. For a detailed review of the attempts to model ε Aur in light of observations up to 2002, see Guinan & Dewarf (2002).

In the time since, infrared astronomy and interferometry in particular has significantly matured. Using the CHARA array, Kloppenborg et al. (2010) directly observed a section of the transiting disc at two epochs during the ingress of the 2009-2011 ε Aur eclipse. After more observations, effectively the complete disc silhouette was imaged and reconstructed (Kloppenborg et al., 2015, top panel in Figure 1) which allowed the authors to select

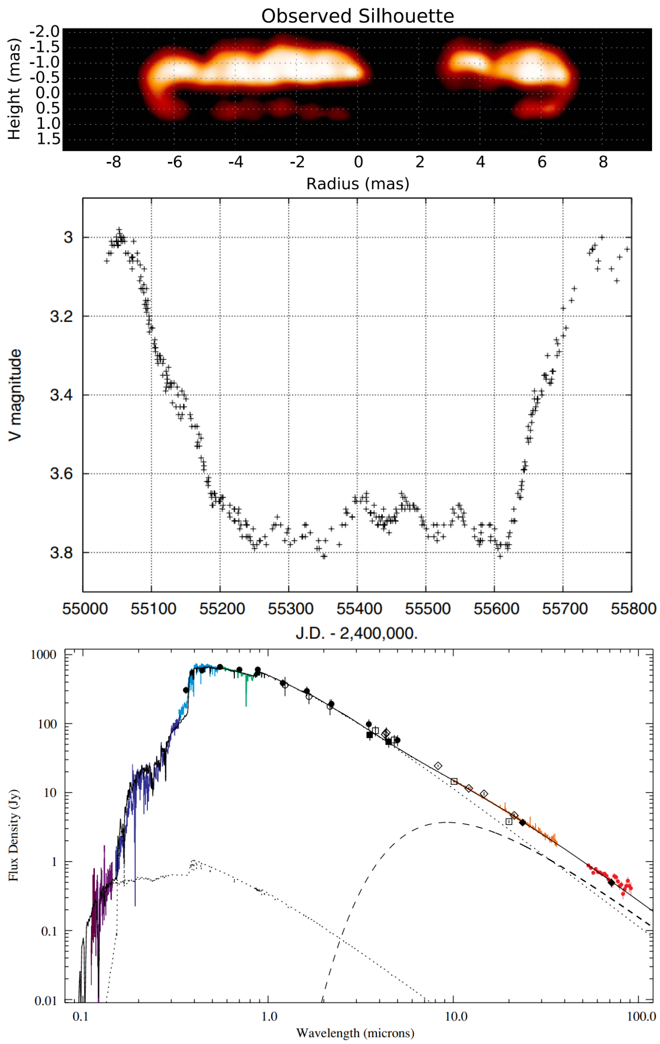

FIG. 1 As the best studied disc eclipsing system to date, there is a wealth of photometric, spectroscopic and interferometric data on ε Aurigae. *Top:* using the CHARA interferometric array, Kloppenborg et al. (2015) was able to reconstruct a semi-complete image of the occluding disc in ε Aur as it transited the F star. This image is the combination of multiple epochs of reconstructions, showing the opaque disc structure moving across the face of the giant star. *Middle:* the 2009-2011 eclipse of ε Aur shows a distinct dip in brightness over $\sim$ 700 days, with several bumps mid-eclipse (Stencel et al., 2011). *Bottom:* The spectrum of ε Aur close to eclipse is well fit by the sum of B5 and F0 spectra together with a cool $\sim$ 550K blackbody (Hoard et al., 2010).

the most likely disc model. This best fitting model is of a slightly tilted disc with a decaying density towards the disc edge, in support of a disc with variable opacity.

Despite the success in explaining some mid-eclipse variability with a variable opacity disc, the prominent mid-eclipse brightening event observed over all previous transits is not so easily modelled. For this, Budaj (2011) modelled the effect of dust grain size and angle dependence of the disc with a radiative transfer code, ultimately suggesting that there exists a larger, optically thin disc of material surrounding the optically thick disc. During transit, this outer disc would scatter light and the strength of this scattering has been used to constrain the inclination of the disc (Muthumariappan & Parthasarathy, 2012).

Aside from physical structure, the disc has been found to have an inhomogeneous thermal profile. Modelling the system spectrum during eclipse shows a clear dependence on a 550 K blackbody to explain the observed mid-infrared flux (Backman et al., 1984; Hoard et al., 2010, bottom panel of Figure 1), a spectral signature attributed to the eclipsing disc. Observing during the transit means that only the region of the disc most distant from the F star (and with significant intermediate material) is visible. Backman et al. (1984) reasoned that the side of the disc facing the star should be of order $\sim$ 1100 K as calculated from the equilibrium temperature of material 30 au from the F0 star. Indeed, Hoard et al. (2012) showed that the spectrum of the disc viewed at opposition has clear signatures of a 1150K blackbody, in good agreement with the disc being heated by the F star (Pearson & Stencel, 2015; Takeuchi, 2011).

Since its discovery, the exact formation mechanism of the secondary's circumstellar disc has been elusive. In particular, uncertainty in distance estimates to the system has fueled longstanding debate as to whether the system is explained by a 'low mass' or 'high mass' scenario (Lissauer et al., 1996). In the former (corresponding to the system being closer), the F0 star would have had a ZAMS mass of $\gtrsim 7M_\odot$ which has since shed mass both through outbursts/winds and through mass transfer to the secondary, now classified as a post-AGB giant. In the latter scenario (for a larger distance), the F0 component is a $15-20M_\odot$ supergiant star near the end its evolution while the B5 star would be of order $\sim 14M_\odot$ (Hoard et al., 2010; Lambert & Sawyer, 1986).

Both through spectral fitting (Hoard et al., 2010, 2012) and evolutionary modelling (Gibson & Stencel, 2018), the low mass scenario has been recently preferred. An independent finding supporting this was in the discovery of a mass transfer stream between the F0 star and the disc, only visible through spectroscopy at a very narrow window in phase after periastron passage (Gibson et al., 2018; Griffin & Stencel, 2013). The best-fit orbit yields an eccentricity of the binary of $e = 0.227$ (Stefanik et al., 2010), which may be the underlying cause of the strong phase sensitivity of the mass stream. As the low mass scenario requires mass transfer between the components, this strongly disfavours the higher mass scenario where the binary stellar evolution is largely non-interacting. Further, Wolk et al. (2010) published a non-detection of X-rays associated with ε Aur effectively ruling out a model in which the disc enshrouds a compact remnant.

The sustained study of the prototypical disc-eclipser ε Aurigae has culminated in an immense body of work encompassing instrumentation, simulation, and theory. All of this research is owing to the simple yet effective geometric model of an extended opaque disc transiting across the face of a bright star. Despite the numerous successes in modelling, however, the evolutionary history and disc formation process of ε Aur is still not firmly understood. There is a gap in the literature of modelling this system from first principles, e.g. with a full hydrodynamical treatment of the mass transfer and dust physics. A rigorous modelling of the disc structure, including any inhomogeneities or warping, has not yet been published, and this is essential to understanding dust formation not only in ε Aur but also in the wider context of evolved stars. More emphasis is needed particularly on the evolutionary history of the system; is a wide binary with an extended dusty disc typical for evolved stars of these masses, or is ε Aur a peculiarity in binary evolution? These unanswered questions remain the biggest mysteries of ε Aur and how it is representative of mass transfer in stellar binary evolution.

B. Post-Main Sequence Systems

In the time since the discovery of ε Aurigae, and especially in the last 10 years, there have been several more disc-eclipsers found. Observing their photometry in isolation makes it difficult to determine whether a disc-eclipsing system is pre- or post-main-sequence, although many of these systems have associated spectroscopic data to aid in characterisation. Those systems found with a post-main-sequence component are particularly interesting from the perspective of evolved binary interactions and as gravitational wave progenitors. The presence of a disc in these systems is a clear signature of mass transfer, and observational constraints on mass transfer inform population synthesis codes, hydrodynamical simulations, and more. How we model binary evolution with these simulations sensitively predicts families of supernova progenitors (via the modelled stellar structure and chemistry at the time of explosion) and subsequently the masses of supernova remnants, correlating with the observed population of gravitational wave observations. Modelling eclipsing discs are essential in this context, as they provide the best constraints on the disc mass and geometry which then propagates into evolution models.

The majority of these evolved disc eclipsers fall, again, into two distinct categories: those of short ($\ll$ 1 year) orbital period resembling stars such as β Lyrae, and those of long periods more resembling ε Aurigae.

1. Short- and Intermediate-Period Systems

Evolved binary stars that orbit with short ($P \lesssim 20$ days) and intermediate periods ($20 \lesssim P \lesssim 100$ days) are of particular interest from a coevolving and gravitational wave/supernova perspective (Sana et al., 2012). Systems containing accreting white dwarfs are expected to eventually undergo a supernova explosion, such as CI Aql in $\sim 10\,\mathrm{Myr}$ (Lederle & Kimeswenger, 2003; Sahman et al., 2013), and closely orbiting massive stars result in (any combination of) neutron star/black hole mergers within the Hubble time (Kruckow et al., 2018). The slightly-less-evolved counterparts of these systems and other stellar remnant binaries are therefore subject to rigorous studies in an attempt to better understand their evolutionary histories.

As perhaps the most famous example of a short period eclipsing binary, the Algol system is the subject of paradoxical characteristics; the more evolved K2IV star has a significantly lower mass than the main-sequence B8V companion (Baron et al., 2012). The solution to this paradox lies in mass-transfer between the components, where the initially higher mass giant evolved into its Roche lobe and subsequently donated mass to the once lower mass star thereby switching the mass hierarchy. The extremely short ~ 2.9 day period of the system presents an impressive eclipsing binary light curve with regular and deep transits, and the binary has been directly imaged showing the geometric distortion of the donor star (Baron et al., 2012).

It is common for persistent accretion discs to exist in Algol-like systems as the donor transfers mass through Roche lobe overflow (RLOF). The ~ 13 day orbital period binary β Lyrae is one such system, where a thick accretion disc obscures the 'gainer' component at all times (Ak et al., 2007; Zhao et al., 2008, for direct images). The β Lyrae accretion disc has been well modelled using photometric data of the transit profiles, but also with spectroscopic and interferometric data which allows inference of the disc temperature profile (among other parameter profiles) as well as the presence of jets (Brož et al., 2021). This type of modelling (together with the system V4142 Sgr, for example; Rosales et al., 2023, and references on other systems therein) unambiguously shows that the temperatures of β Lyrae type accretion discs are too high to host dust formation, apparently unlike long period systems such as ε Aur. This is corroborated by a distinct double peaked hydrogen-alpha emission in these systems, indicative of a rotating accretion disc; these features are routinely modelled to understand disc dynamics and temperature (Atwood-Stone et al., 2012; Desmet et al., 2010, for examples modelling AU Mon).

The key difference that the accretion disc imposes on the light curve is a more extended, smooth transit across the primary eclipse. For such close systems, the donor filling its Roche lobe smooths the secondary eclipse as a result of geometric effects (Huang, 1963; Wilson, 2018). Since the stars are so close together, reflection effects are essential to include in light curve models although the accretion disc can influence the effect of this depending on its opacity and geometry (Pavlovski et al., 2006; Wilson, 1990). These close binary systems also have largely circularised orbits (mostly due to tidal effects, Moe & Di Stefano, 2017; Zasche et al., 2018) which result in half-phase separated primary and secondary eclipses (although there has been at least one discovery with a non-zero eccentricity of $e \simeq 0.021$ in Miller et al., 2007). Despite the consistency in conditions over a circular orbit, there has been at least one system (OGLE-LMC-ECL-17782, Graczyk et al., 2011) observed with a variable transit profile which is indicative of changing conditions.

Opening the parameter space to so called 'intermediate' period binaries (of order $20 - 100$ days) introduces more exotic systems than is often seen in the short period cases. One particular system is TT Nor ($P = 37.35$ days) which has a clearly eccentric orbit as a result of its unequally spaced light curve eclipses (Rowan et al., 2023). Together with the simultaneously reported light curve of star OGLE-LMC-ECL28271 ($P = 27.11$ days), these transits display eclipse profiles largely like the typical thick, opaque discs that are suggestive of disc physics more in line with ε Aur than bright accretion discs. Notably, many of these intermediate period orbiters effectively have no (or a very minor) secondary eclipse which constrains the brightness of the circumstellar disc component (e.g. in the 'forgotten' system RV Aps, Debackere et al., 2020; Khaliullin et al., 2006, or in MWC 882, Zhu et al., 2022)

The idea of system with a non-circular orbit poses interesting questions about the stability of the mass-transfer accretion discs in short-period systems. Mennickent & Djurašević (2021) reported a finding of a variable transit profile in the system OGLE-BLG-ECL-157529 on a timescale of 18 years, despite an associated orbital period of 24.8 days. The authors attribute the variability over successive transits to a changing disc thickness associated with inconsistent mass transfer rates. An appreciable eccentricity is expected to result in highly phase-dependent mass transfer events, which should affect the binary evolution substantially (Davis et al., 2013), even so far as accelerating the overall mass-transfer.

While RLOF occurs, orbital angular momentum conservation dictates that the orbital separation (and hence the period) must increase between the stars (Zhou et al., 2018). This has been used to explain presently large orbital periods in what are understood to be post-Algol systems (i.e. where mass transfer is no longer appreciably taking place). This raises the question, however, of how accretion discs remain in systems that are too far separated for RLOF to occur, such as in MWC 882 (Zhou et al., 2018).

2. Long-Period Systems

The mystery of the persisting lifetimes of circumstellar discs in post-main-sequence systems is further complicated for those systems of orbital periods $P \gtrsim 100$ days. Even for the largest giant stars, the binary is often well detached and no classical RLOF is expected to occur.

For the long period disc eclipsers, the observed distribution of orbital periods seems to peak in the range 100 days $\lesssim P \lesssim 5$ years, although the distribution has a long tail. Recently, some systems have been found that dwarf the period of ε Aur in comparison. In particular, the M giant system TYC 2505-672-1 has an apparent orbital period of ~ 69.1 years (Lipunov et al., 2016; Rodriguez et al., 2016), a factor 2.5 times longer than ε Aur. Other candidate super-long-period eclipsers have been observed too, namely VVV-WIT-08 where one transit was observed in a densely time sampled ~ 20 years (Smith et al., 2021), and Gaia17bpp having observed the longest transit dimming event so far at over 6.5 years (Tzanidakis et al., 2023). The latter discovery is suggestive of a much longer period, considering that transit events have only ever been attributed to somewhat narrow orbital phase windows.

These two systems are uniquely poised to highlight the observational biases associated with discovering and studying these extremely long period eclipsers. Photometry of a broad range of targets has only been available for ~ 100 years or so, with precise data (needed to quantify transit peculiarities for example) only being obtained recently. For a strong constraint on orbital period, two primary eclipses (corresponding to just over one full orbit) must be observed, and so our historical timescale of observation is a major limiting factor in these systems characterisation. On a similar note of observational bias, there are geometric considerations which tend to hide these systems from our view. Assuming that an increase in orbital period directly corresponds to an increase in semi-major axis (which is not always the case and depends directly on the mass of the system), the inclination of the binary must get closer to 90° for a transit to be visible. This is because as the binary components get more distant, their apparent sizes approach unity which reduces the possible orbital configurations resulting in a transit. These biases do not just apply to disc-eclipsers, but to transiting exoplanets and all eclipsing binaries; the true population of these class of system is in truth much larger than we are capable of observing with photometry alone.

Interestingly, many of these long period disc eclipsers have been observed with an eccentricity much higher than their low period counterparts (van Winckel, 2003). This could suggest periodic mass transfer such as was seen in the ε Aur system (Griffin & Stencel, 2013). Whether the periodic mass transfer and subsequent disc is a symptom of the binary evolution or whether it is the driving force

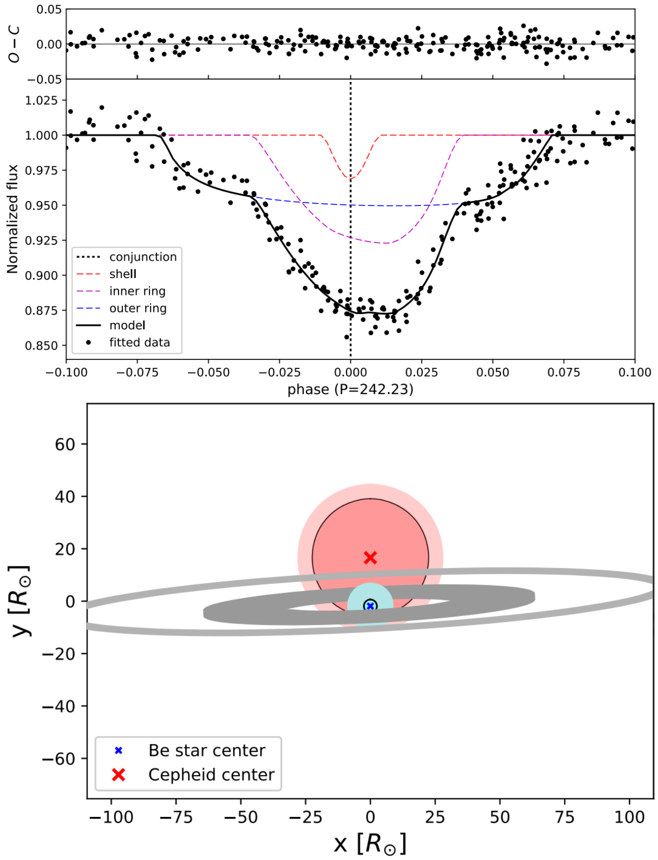

FIG. 2 The OGLE-LMC-T2CEP-211 system is well described by the simultaneous eclipse of two circumstellar rings. *Top:* The light curve of OGLE-LMC-T2CEP-211 during transit shows a distinct 'double dip' structure of different depths. *Bottom:* The physical picture of the modelled eclipse profile shows a thin outer disc and thick inner disc. Both figures from Pilecki et al. (2018).

is not clear; detailed simulations of the formation and maintenance of these discs are sorely needed.

One possible mechanism proposed for mass transfer in wide, long orbital period binaries is the wind Roche lobe overflow (WRLOF; Mohamed & Podsiadlowski, 2007). This has been shown to provide efficient mass transfer in well-detached binaries with orbital periods of order years to tens of years (Sun et al., 2024), and has been used to explain the observed dust discs around some systems (e.g. Hinkle et al., 2022; Sanchez Contreras et al., 2022) and even the distorted circumstellar discs inferred around some disc-eclipsers (Saladino et al., 2019). More hydrodynamical simulations that include dust and radiative modelling is needed to determine the exact role of dust formation via mass transfer in these systems, however.

Another mechanism for disc formation in at least some of the systems described in Table I lies in the Be star 'decretion disc' phenomenon. Be stars are believed to be almost critically rotating, forming a disc of material extending away from the equator that is supplied by either continuous or episodic mass loss (Rivinius et al., 2013, for a review). These decretion discs are an attractive explanation for those disc eclipsing systems of especially long periods (and therefore with well detached stars) and/or where efficient mass transfer is not necessarily expected at the current stage of binary evolution (e.g. in a pre- or post-giant phase). When in binaries, these decretion discs are expected to be dynamic and geometrically evolve on timescales of months to years (Marr et al., 2022), possibly describing some of the more exotic eclipsing disc configurations.

The prevalence of complex structure in circumstellar discs, be it warping, asymmetry, or multiple structures (e.g. rings of material), is not yet well understood. Several systems observed so far have been observed to have asymmetric transit profiles (see Table I) which indicates substructure within the transiting disc; phenomena such as opaque plus translucent disc components (e.g. ε Aur or OGLE LMC-ECL-11893, Muthumariappan & Parthasarathy, 2012; Scott et al., 2014, respectively), multiple concentric discs of different properties (e.g. OGLE-LMC-T2CEP-211, Pilecki et al., 2018), or tilted/elliptical discs (Smith et al., 2021, e.g. VVV-WIT-08,) are commonly modelled to explain observed transit profiles. A spiral-like structure in addition to a dusty disc has been observed in the V Hya system also, which presents a challenge to model (Knapp et al., 1999; Planquart et al., 2024b). To some extent, these different physical explanations share various degeneracies in how well they explain observations, and more data of a different type (e.g. spectra) is needed to distinguish between models.

Although some systems show deviation from a 'standard' symmetrical eclipse profile, the majority of these eclipses are static in time. A rare subset of the long-period disc eclipsing systems have been observed to have a varying transit profile over successive orbits. Perhaps the most high profile dynamic disc eclipser is EE Cephei, whose transits have unique profiles and different depths on each observed eclipse over the last 50 years of observations (Pieńkowski et al., 2020). To explain this, Mikolajewski & Graczyk (1999) suggested that the circumstellar disc surrounding the companion is precessing such that the geometry of occultation changes on each eclipse. This is a common explanation for observed variability in eclipse profiles, although the preferred mechanism for EE Cephei's inconsistency is now that the Be primary (which is occulted) is precessing: the occluded geometry of the highly oblate and gravity darkened star is sensitive to the (assumed static) disc and produces varying eclipse profiles (Pieńkowski et al., 2020).

While the phenomenology of EE Cephei is well modelled, other systems with varying transit profiles are not necessarily so. Rattenbury et al. (2015) introduces the system OGLE-BLG182.1.162852 which shows an extremely asymmetric profile that varies in egress on each

System	Period	Notes	Source
W Crucis	199 d	G1 Iab + B?V	Pavlovski et al. (2006)
ELHC 10	220 d	F3-6 + ?, circumbinary + circumstellar discs	Garrido et al. (2016)
OGLE-LMC-T2CEP-211	242 d	G1 II + B?V, Type II Cepheid variable	Pilecki et al. (2018)
ZTF J185259.31+124955.2	290 d	K0-4 III + ?, variable transit profile	Bernhard & Lloyd (2024)
OGLE-LMC-ECL-11893	1.28 yr	?+B9 IIIe, asymmetric transit profile	Dong et al. (2014); Scott et al. (2014)
OGLE-BLG182.1.162852	3.5 yr	K giant + ?, variable transit profile	Rattenbury et al. (2015)
EE Cephei	5.6 yr	Be + ?, variable transit profile/depth	Pieńkowski et al. (2020)
KIC 5273762	7.3 yr	M? giant + ?, asymmetric transit profile	Jayasinghe et al. (2018)
η Gem	8.2 yr	M3.5 Ib + A0-5V ?, photometric variability hierarchical triple	Torres & Sakano (2022)
ASASSN-21co	11.9 yr	M + M/?, Unconfirmed disc	Rowan et al. (2021)
V Hya	16.9 yr	M + ?, Mira variable	Planquart et al. (2024a)
ε Aurigae	27.1 yr	F0Ia + B5V	Stencel et al. (2011)
R Aquarii	43.6 yr	M6-9 + WD, Mira variable	Hinkle et al. (2022)
TYC 2505-672-1	69.1 yr	M2 III + sdB	Rodriguez et al. (2016)
VVV-WIT-08	?	K7-M2 giant + ?	Smith et al. (2021)
Gaia17bpp	?	K5 III or M0 III + ?	Tzanidakis et al. (2023)

TABLE I List of long-period, evolved disc-eclipsing binaries, sorted by orbital period.

orbit. Due to the poorly sampled and scattered data, it is unclear whether the η Geminorum system (Torres & Sakano, 2022) also belongs to this class of system with inconsistent transit profiles. Of particular interest is the system ZTF J185259.31+124955.2, whose transit has been observed to broaden in time on each successive eclipse from 2017 to 2023, while the transit has maintained the same depth unlike other systems (Bernhard & Lloyd, 2024). The reason for this may be entirely different from the other varying systems, and more study is needed to understand the underlying physics of all of these systems.

While many of the discussed systems are too low-mass to be gravitational wave progenitors, the remaining systems form convincing Type Ia supernova progenitors. With that said, the determination of the masses of each component is a laborious task and the associated errorbars often do not discount the possibility of neutron star end-products. In any case, there have been several disc bearing systems that are associated with planetary nebulae and SNe Ia, either at present or expected in the future. The planetary nebula EGB 6 is believed to be a post-Mira binary system composed of white dwarf with an apparent dust-enshrouded star and several low-temperature blackbodies (Bond et al., 2016). Conversely, the system R Aqu is believed to be a symbiotic binary where a WD has a dusty obscuring disc as a result of accretion from a companion Mira (Hinkle et al., 2022). Given that the obscured component in these eclipsing disc binaries is fundamentally obscured, more of these systems may contain a WD embedded in an accretion disc.

Especially in those systems with one observed eclipse, follow-up and routine observation is necessary to understand the physics of the disc-eclipsing systems. More eclipse observations of VVV-WIT-08 or Gaia17bpp may reveal varying transit profiles, for example.

C. Pre-Main Sequence Systems

While evolved stars compose the majority of observed disc-eclipsing systems, they are by no means the only examples. By now, several pre-main-sequence binaries have exhibited similar transits to those of their evolved counterparts. The underlying physics describing these pre-main-sequence systems is fundamentally different and worth exploring, especially to describe their observational differences. Pre-main sequence stars are the near-to-end results of the collapse of massive gas clouds; as a result, discs are expected to form around the collapsing stars due to angular momentum conserved from the original cloud (Andrews, 2020). This provides a logical formation channel for discs around such young stars with minimal exotic physics needed. Protoplanetary discs around single stars are a well studied phenomenon, revealing the ingredients and dynamics of planet formation. Around binary stars, however, this process is less well understood and invokes extra layers of dynamic complexity. Observa-

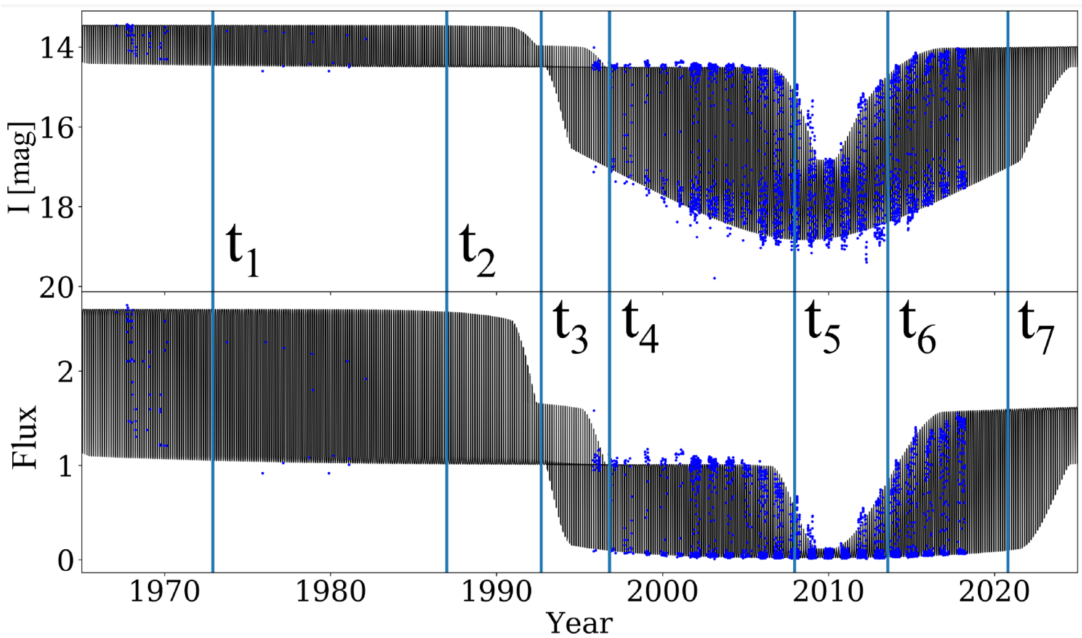

FIG. 3 The light curve of KH 15D clearly shows an evolving eclipse profile over the last 50 years. The modelled precessing circumbinary disc model (black line) very accurately reproduces the observed photometry of the system (blue markers). The vertical lines indicate times at which the binary orbit encounters different geometric regions of the disc. Figure from Poon et al. (2021).

tions of young disc eclipsing systems, then, are a valuable tool in precisely studying the disc structures that gives rise to planets in dynamically unstable environments (see section 3.2 in Andrews, 2020).

The young disc-eclipsing binary systems are dim in comparison to their evolved counterparts that have at least one component occupying the upper regions of a colour-magnitude diagram. Further, the environment around these young systems is often rich with gas and dust which obscures the stars in the optical, often only revealing them in the near-to-mid infrared. As a result, the discovery of these objects has been a relatively recent phenomenon and the observed population is somewhat small.

One interesting system observed so far is the binary Gaia21bcv. This system consists of a K4-type pre-main-sequence primary and an extremely long-eclipsing, disc-enshrouded secondary (Hodapp et al., 2024). The transit lasted approximately 800 days and had mid-eclipse flux variability indicative of a non-uniform optical depth or substructure.

Asymmetry in the eclipse profiles of these young systems is also common, suggesting non-planar geometry or inhomogeneous material. Such an eclipse is seen in the V928 Tau system, whose short transit is explained by a transiting circumstellar/planetary disc around a massive ($\sim 80 M_J$) companion on an eccentric orbit (van Dam et al., 2020). On a similarly eccentric orbit is EPIC 220208795, a K dwarf primary with the smallest known isolated transiting dust disc (van der Kamp et al., 2022). Both of these systems are expected to have a relatively low mass transiting object within the dust disc, and the disc formation mechanism is unclear for such eccentric orbiters.

Instead of circumstellar discs around pre-main-sequence stars, what are more commonly observed are the circumbinary disc eclipsers; in these systems, the two component stars have carved a cavity within a much wider natal disc and their interactions and orbits can result in one or both stars periodically moving to behind the disc from our perspective.

The prototypical circumbinary disc eclipser is the T Tauri binary KH 15D, first identified as a circumbinary disc in 2001 (Hamilton et al., 2001; Kearns & Herbst, 1998). In this system, the two young pre-main-sequence stars embedded within the disc are on an eccentric orbit, where one of the two stars is periodically occluded by the wider disc. The transit profile from the disc was quickly observed to be evolving, however, and eventually there existed an ever-increasing phase window where both stars were occulted (Hamilton et al., 2005). The proposed explanation for this successively widening transit is that the circumbinary disc is warped, inclined, eccentric, and with the key property that it is precessing (Winn et al., 2006). This disc model reproduces the observed photometry excellently (Figure 3 from Poon et al., 2021, which also reviews previous modelling), and offers valuable insight into the physics of warped discs and young systems.

Similar eclipse profiles to KH 15D have been seen in other systems, both those of the evolving and static variety. OGLE BLG-DN-652 shows such a profile which is slightly evolving over time ("Source 207" in Lucas et al., 2024), as does WL 4 (Plavchan et al., 2008) and ONCvar 149 (Rice et al., 2015), and this indicates intrinsic or geometric evolution in the circumbinary discs of these systems. Interestingly, several systems have been observed with consistent profiles (at least since their discovery). Such systems include YLW 16A (Plavchan et al., 2013), Bernhard-1 and Bernhard-2 (Zhu et al., 2022), ONCvar 1226 (Rice et al., 2015, whose quoted period may be too low by a factor 2), and CHS 7797 (= ONCvar 479, Rodríguez-Ledesma et al., 2012), although continued monitoring of these systems may reveal profile variability.

Out of the candidate disc-eclipsers, V718 Persei stands out as a peculiar system. The late-type G/K pre-main-sequence primary periodically undergoes the longest eclipse observed for such systems, with an eclipse duration of 3.5 years out of its 4.7 year orbit (Cohen et al., 2003; Nordhagen et al., 2006). The transit profile is largely asymmetric and apparently features just one deep eclipse, unlike systems such as KH 15D. The literature on V718 Persei has largely stagnated and so the orbit-on-orbit variability, if any, is unclear. The occulting 'object' has been proposed as a extended mass distribution along a circumstellar disc (making V718 Persei a single star system; Grinin et al., 2008), and also a circumbinary disc such as in KH 15D (Nordhagen et al., 2006).

While circumbinary disc eclipsers may be the most intuitive explanation for these events, there exist other phenomena that have been linked to observed dips in flux. The system RW Aurigae is a confirmed binary where each component has their own circumstellar disc; on a recent periastron passage, the gravitational perturbation to the disc of the primary resulted in a tidal arm of material which is believed to 'transit' the star (Rodriguez et al., 2013). Similarly, a warp in the inner accretion disc of the classical T Tauri star AA Tau is believed to periodically obscure the central star in a quickly evolving profile (Bouvier et al., 2007). Some of the observed dips in flux may also be explained by transiting of accretion streams onto one or both of the stars in young binary systems from the circumbinary disc (Grinin et al., 2010).

Finally, Kenworthy et al. (2022) introduce a transiting circumbinary disc in the hierarchical multiple system V773 Tau to explain an asymmetric transit seen in 2010. This forms a unique intersection of the discussed phenomena so far; the provided explanation is a circumbinary disc around the Ba and Bb components of the system, where the disc transits across the observed Aa and Ab components. Further observation of this system up to and during the predicted 2037 eclipse are essential to understand disc formation and maintenance in such a complex hierarchical system.

III. PLANETARY RING ECLIPSING SYSTEMS

Although there are currently no circumstellar discs in our own solar system, similar geometry is found in the rings of the gas giant planet Saturn (and to a lesser extent the other gas giants). With this in mind, when viewed from another star system we might expect that the transit of Saturn would impose similar dipping features in the Suns light curve (Barnes & Fortney, 2004). Since the known planetary rings are composed of not one but several concentric rings, modelling this then becomes analogous to modelling systems such as OGLE-LMC-T2CEP-211, i.e. with the superposition of multiple thin discs at once (Pilecki et al., 2018). Modelling the transiting rings as (semi-)opaque discs carries with it the same positives as does modelling transiting circumstellar/binary discs: we are able to sensitively constrain the geometric properties of the discs with fast statistical methods where hydrodynamical or radiative modelling would be intractable.

In the last $\sim$ 10 years, a handful of convincing circumplanetary discs and 'exoring' systems have been discovered and characterised. The first unambiguous detection was in the system 1SWASP J140747.93-394542.6 (= V1400 Centauri, hereafter J1407) by a ringed planet J1407 b (Mamajek et al., 2012). The defining characteristics of this eclipse were an extended, $\sim$ 56 day duration, as well as several tens of small flux minima and maxima. The duration of the eclipse together with later observed radial velocity measurements of the host star allowed for a parameter space constraint on the mass and period of J1407 b, effectively confirming a massive planet (or low-mass brown dwarf) as the center of the ring system (Kenworthy et al., 2015). The extremely complex transit profile (see bottom panel of Figure 4) provided evidence of concentric ring structure for which tens of rings of varying opacity make up the whole ring system (Kenworthy & Mamajek, 2015; van Werkhoven et al., 2014).

The ring system of J1407 b has been suggested to be in a transitional state, since the measured radius is approximately 0.6 AU – well beyond the Roche limit of the planet – and so should not be stable over astronomical timescales. This ring system, and those around other planets, are likely formed by satellite collisions especially those in young systems such as J1407 (Mustill et al., 2024; Teodoro et al., 2023). In this way, constraining the ring parameters informs us of the dynamics of circumplanetary environments (i.e. how many planet/satellite collisions occur and what are their compositions) where we would otherwise have no way to probe them with such detail.

The presence of satellites around J1407 b is further supported by the multiple large gaps in the ring system which has been linked to exomoons on stable orbits (Kenworthy & Mamajek, 2015; van Werkhoven et al., 2014). The possibility of detecting the transit signature of ex-

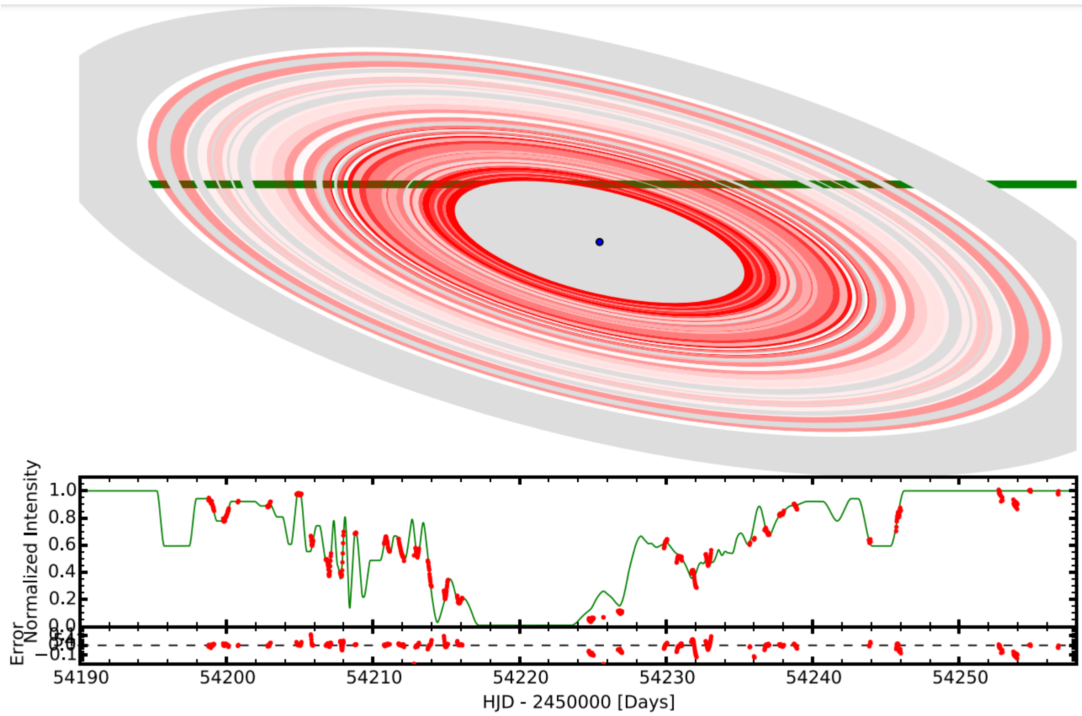

FIG. 4 The observed transit of J1407 b shows complex structure indicative of a rich circumplanetary ring system. The best fit model utilises concentric rings of changing opacity and width, with gaps between rings where needed to explain local flux maxima; these rings systems can be modelled by software, e.g. that in van Dam & Kenworthy (2024). Figure from Kenworthy & Mamajek (2015).

omoons themselves embedded within the ring systems has not been explored, and would prove difficult breaking the degeneracies between the signal of a moon and an additional ring. The transit signature of an exomoon has been claimed in Kepler-1708 b-i, however, and so repeated transits are necessary to disentangle the signals (Kipping et al., 2022, and for a chapter on exomoon detection see Teachey, 2024).

As of the time of writing, a second transit of J1407 b has not been observed which narrows the allowable orbital period and mass parameter space of the planet. In this way, non-detections of events contribute some information which improves our understanding of these systems. A non-detection of a repeating anomalous dimming of β Pictoris allowed the constraining of the amount of dust in the Hill sphere of a giant planet at ~ 10 au (Kenworthy et al., 2021), and given that the population of these protoplanetary disc/ring eclipsers are so few, these objects warrant continued observation and interest.

While J1407 b is the prototypical ring eclipser and by far the most rigorously studied, there have recently been new discoveries of extended transits due to circumplanetary material. The next best observed system is PDS 110, where two deep and consistent transits were observed in 2008 and 2011. The transit profiles were similarly chaotic to J1407 b and showed largely similar phenomenology to each other, indicative of a structured ring system around a planetary companion (Osborn et al., 2017). Unfortunately, with a predicted orbital period of ~ 2.2 years, there was a non-detection of the expected 2017 transit; this implies that a single ringed planet is not the explanation for the earlier observed events (Osborn et al., 2019) especially given that inclined discs are expected to survive for order $\gtrsim$ Myr (Speedie & Zanazzi, 2020).

The star VVV-WIT-007 was suggested to have a protoplanetary or ringed companion on account of the possibly periodic deep dipping in its light curve (Saito et al., 2019). Several dips were observed over a few years of observation, albeit without dense time sampling and so there exists ambiguity in the exact period of the transits, if it even is periodic. Still, the phase-folded light curves of the system show asymmetry and hints of complex structure which warrants further study.

ASASSN-21js is the most recently discovered ring-eclipsing system, whose light curve shows extreme asymmetry and complex structure (Pramono et al., 2024). Although the transit is ongoing at the time of writing, the duration so far of ~ 3 years indicates a uniquely large ring situated very far from the host star. Although some rings have been seen around distant minor bodies in our solar system (e.g. Braga-Ribas et al., 2014; Pereira et al., 2023), having such a large distant ring presents an interesting challenge to explain.

All systems discussed so far have been suggested to have large ring systems of order 1 au in size. One candidate ring system around KIC 10403228 has been modelled with a comparatively small, titled, and opaque ring around a planet which notably reproduces the observed asymmetry in the transit profile (Aizawa et al., 2017).

The young M-dwarf system EPIC 204376071 has exhibited a dip characteristic of a protoplanetary disc (Rappaport et al., 2019). Disparate to the other systems mentioned, the transit profile is smooth although asymmetric and hence does not show evidence of a ring. Its comparatively short transit duration of ∼1 day effectively rules out a possible companions large circumstellar disc, but is too long to be described simply by the disc of a planet or star. The proposed mechanism for the transit is a $\sim 3M_J$ planet with a circumplanetary disc of dust. As with all of the mentioned planetary systems so far, only one transit has been observed so far and regular monitoring is essential to learning more.

Finally, a ring around the planet HIP 41378 f has been proposed to explain the observed transit that would imply a planet size abnormally large for its mass. With a planet density of $0.09\,\mathrm{g\,cm^{-3}}$ calculated in a no-ring model, the planet would be entirely unlike any previously found especially for its 542 day orbit around an F6 host star (Akinsanmi et al., 2020). The introduction of an almost face-on ring solves this problem by sharing the contribution to the transit depth, essentially allowing the true planet radius to be much smaller and hence making for a denser planet. The fit values would suggest a planet similar to Uranus in inclination, mass, and size.

Photometric observation is the most common tool to discover ring systems around planets, but spectroscopic observations of stars during transits may indicate ring structure also. Ohno et al. (2022) introduce this idea as an application to the K2-33b system, whose transmission spectra during transit were not adequately explained by physics intrinsic to the stellar or planetary surface. Not only as a tool to understand the presence of ring systems, transmission spectroscopy can in principle be used to understand the composition of ring systems with sensitive enough observation. For this, the James Webb Space Telescope is uniquely situated to provide the first data on ring spectra during transits, and may be the only telescope in operation sensitive enough to detect contribution from rings (Alam et al., 2022; Ohno et al., 2022).

Features on the surface of stars, such as star spots, also impact the light curve of a star as they rotate in and out of our view. While these are typically not confused for planet transits, in principle they can affect the transit profile of a planet and its rings. In this case, the transit profile can then reveal information about the size and location of star spots on the stellar surface if the baseline transit profile is well modelled (Davenport et al., 2015). If repeated eclipses of ringed planets are observed, and the ring structure is stable over dynamical timescales, these ring transits could potentially be used to create extremely precise, unique maps of the stellar surface. Hence studying exoring systems is not only beneficial in the context of exoplanets and moons, but also in the understanding of stellar activity and therefore habitability (Airapetian et al., 2020).

IV. OUTLOOK

Through years of wide-angle photometric observation, a number of transient disc-eclipsers have been observed with a range of underlying physical interpretations. These phenomena present themselves through extended and often asymmetric and complex transit profiles of host stars, and so high cadence, regular observation of a wide range of stars is important to characterise the total population of disc and ring eclipsers.

In the near future, the Vera C. Rubin Observatory will take first light and begin surveying the southern sky for transient phenomena. The Rubin Observatory will collect orders of magnitude more data each night than previous state-of-the-art survey missions, monitoring not just extragalactic transient phenomena but stars in our own galaxy too. As such, we should expect to have access to orders of magnitude more data on potential disc and ring eclipsers that have so far eluded discovery. The problem then becomes how to design an automatic alert system which sorts through the data to yield accurate notifications of disc/ring transits in progress. If this is successful, we may see a surge in disc/ring eclipsers akin to the exoplanet discovery explosions associated with *Kepler* and TESS.

The prospect of these systems ‘hiding’ within archival data, yet to be found, is a certainty also. In designing an alert system for future surveys, we may be able to retroactively apply it to archival data of the TESS, *Kepler*, OGLE, ASASSN, ZTF, etc, surveys to obtain not only new discoveries but the essential constraining power that comes with long timescale observations.

In having better observations over longer periods, we can more thoroughly understand the evolution of these processes: how does periodic mass transfer in evolved systems warp and change the structure of circumstellar discs; how do planets form in protostellar discs around binary and hierarchical pre-main-sequence systems; can exomoons be detected embedded within exorings and are those rings stable on dynamical timescales.

The technical achievements of modelling ε Aurigae have overhauled our understanding not only of evolved binary evolution, but also the structure of circumstellar material and its composition. This has had wide-reaching effects not just in stellar evolution, but in the modelling of planet formation, the dynamics of stars and planets, and how that affects their environments. With the recent success of wide-field photometric surveys and the upcoming next-generation telescopes, much about eclipsing disc and ring systems is beginning to be understood with rich implications for the future of stellar and planetary evolution models.

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