Low-Mass and Sub-stellar Eclipsing Binaries in Stellar Clusters

Nicolas Lodieu, Ernst Paunzen, and Miloslav Zejda

Contents

Abstract We highlight the importance of eclipsing double-line binaries in our understanding on star formation and evolution. We review the recent discoveries of low-mass and sub-stellar eclipsing binaries belonging to star-forming regions, open clusters, and globular clusters identified by ground-based surveys and space missions with high-resolution spectroscopic follow-up. These discoveries provide benchmark systems with known distances, metallicities, and ages to calibrate masses and radii predicted by state-of-the-art evolutionary models to a few percent. We report their density and discuss current limitations on the accuracy of the physical parameters. We discuss future opportunities and highlight future guidelines

N. Lodieu (✉)
Instituto de Astrofísica de Canarias (IAC), La Laguna, Tenerife, Spain

Departamento de Astrofísica, Universidad de La Laguna (ULL), La Laguna, Tenerife, Spain
e-mail: nlodieu@iac.es

E. Paunzen · M. Zejda
Department of Theoretical Physics and Astrophysics, Masaryk University, Brno, Czech Republic
e-mail: epaunzen@physics.muni.cz; zejda@physics.muni.cz

P. Kabáth et al. (eds.), *Reviews in Frontiers of Modern Astrophysics*,
https://doi.org/10.1007/978-3-030-38509-5_8

to fill gaps in age and metallicity to improve further our knowledge of low-mass stars and brown dwarfs.

1 The Importance of Eclipsing Binaries

1.1 Scientific Context

Low-mass M dwarfs are the most common stars in the Solar neighbourhood and, more generally, in the Universe, accounting for about 70% of the entire population of hydrogen-burning stars with masses below 0.6 $M_{\odot}$ [1, 2]. Determining their physical parameters (luminosity, mass, radius) is fundamental to understand stellar evolution and constrain theoretical isochrones. At lower temperatures, the numbers of brown dwarfs, objects unable to fuse hydrogen in their interiors [3–5], with accurate mass and radius measurements remain very limited.

Eclipsing binaries (EBs) are systems with two components lying on the same plane with respect to the observer transiting each other periodically. They are fundamental probes of stellar evolution and stellar candles to measure distances of clusters [6] because the radius and mass of each component can be derived with high precision from the photometric light-curves and radial velocity monitoring, respectively [7].

The numbers of EBs has increased dramatically over the past two decades thanks to the advent of large-scale photometric and spectroscopic surveys as well as space missions. Following up on the original reviews on fundamental parameters of stars derived from EBs [8, 9], a catalogue of detached EBs with their main physical parameters including masses and radii determined to precisions better than a few percent is constantly updated [10].[1] Another public databases with physical parameters of EBs is the Binary Star Database [11],[2] which contains physical and positional parameters of the components of 120,000 stellar multiple systems compiled from a variety of published catalogues and databases.

Other unrelated projects contributed, currently supply, and will add to our knowledge of EBs. As a few example, the OGLE project principally devoted to microlensing provides huge amount (several hundred thousands) of eclipsing systems over a wide range of mass and evolutionary states towards the Galactic Bulge [12].[3] The All Sky Automated Survey (ASAS)[4] is a low cost project dedicated to constant photometric monitoring of the full sky to study variable phenomenon of any kind, including the study of EBs [13]. The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) is a large Chinese project dedicated to

---

[1] The catalogue is maintained at http://www.astro.keele.ac.uk/jkt/debcat/.

[2] The Binary Star Database can be found at http://bdb.inasan.ru/.

[3] http://ogle.astrouw.edu.pl/.

[4] http://www.astrouw.edu.pl/asas/.

spectroscopy of several millions of stars with spectral classification. This program has brought several thousands of EBs over a wide range of spectral type [14], with some masses and radii determined for a few low-mass systems [15]. Other programs mainly dedicated to the discovery and tracking of minor bodies, such as the Catalina Sky Survey [16–18][5] or the Asteroid Terrestrial-impact Last Alert System (ATLAS) project [19][6] do regularly contribute to the discovery of EBs.

This review focuses on low-mass EBs with at least one M dwarf or sub-stellar companions members of star-forming regions (Sect. 2), open clusters (Sect. 3), and globular clusters (Sect. 4). We discuss the frequency of EBs in clusters and the impact of age, metallicity, and stellar variability/activity on their physical parameters (Sect. 5). This review is timely due to the most recent contribution of the *Kepler K2* mission [20, 21] to our knowledge of low-mass EBs in clusters, whose masses and radii can directly be confronted to model predictions. The study of EBs requires huge observing time investment on both photometric and spectroscopic sides needed to infer masses and radii, as demonstrated by the WIYN cluster survey [22–24], the Young Exoplanet Transit Initiative (YETI) focusing on young clusters [25], the Palomar Transient Factory survey [26, 27],[7] and the *Kepler K2* mission. We finish this review with a list of requirements and prospects to fill in gaps in the Hertzsprung-Russell (H-R) diagram (Sect. 6).

1.2 How Masses and Radii Are Determined Observationally

The first attempts to determine the parameters of eclipsing binaries and their components were done in the end of nineteenth century. Up to late 1960s and 1970s year a series of method were developed and used on light curves and radial velocity curves series to subtract and interpolate data from tables of different quantities (more details in [28] or [29]). The spread of computers fasten the development of many codes such as EBOP(Eclipsing Binary Orbit Program) [30], SEBM (Standard Eclipsing Binary Star Model) [31–33], WINK [34–36], LIGHT2 [37, 38], version of WUMa [39, 40] and others.

In 1971, Wilson and Devinney published the results of their code (hereafter WD) where they used for the first time the least-squares method to extract the parameters of light curves [41–44]. This WD code has been regularly upgraded up to now and could be downloaded from author's ftp.[8] Independently, users created graphical user interfaces and some minor upgrades. However, the project PHOEBE [45] is not only GUI for calculations based on WD core, nowadays it has become a more general code to models both the photometric light curve and radial velocity curves of

[5] https://catalina.lpl.arizona.edu/.

[6] https://atlas.fallingstar.com/.

[7] https://www.ptf.caltech.edu/iptf.

[8] ftp://ftp.astro.ufl.edu/pub/wilson/.

eclipsing binaries. The new version of PHOEBE2, which is still under development,[9] contains more physics and improved mathematical methods for the solutions of eclipsing binaries [46–48].

Independent codes like MECI (Method for Eclipsing Component Identification) and DEBil (Detached Eclipsing Binary Light curve fitter) [49, 50], EBAS (Eclipsing Binary Automated Solver) [51, 52], FOTEL [53], JKTEBOP,[10] ROCHE [54], NIGHTFALL,[11] BINARY MAKERS (BM) [55] are used in limited numbers of publications. Two authors of these codes also collect binary stars solutions—David H. Bradstreet, author of Binary Maker, manages the Catalog and AtLas of Eclipsing Binaries (CALEB) based only on BM solutions[12] and John Southworth the DEBCat catalogue,[13] which contains physical properties of well-studied detached eclipsing binaries where errors on the mass and radius determinations are mostly below 2%.

From the aforementioned codes, we can estimated the physical parameters of each component of a multiple system. The main parameters derived from the analysis of the light curve(s) are orbital period, (possibly) eccentricity, orbital inclination, relative ratio of the radius of the primary and secondary of the system considering the separation of the components (top panel in Fig. 1), system luminosity and photometric mass ratios. However, in some cases photometric mass ratios might be unreliable in comparison to spectroscopic mass ratios [57, 58].

The light curve solution usually requires photometric data in at least two filters. The availability of only one passband data means that some of parameters must be estimated and/or fixed. The effective temperature of primary is inferred from its spectral type or colour indices. Limb darkening coefficients are interpolated from tables e.g. [59], gravity brightening and bolometric albedo coefficients are set according to the expected type of stellar atmospheres. Then, except for the parameters mentioned above, one can determine the surface potentials, the rotational/orbital synchronicity, and the third light.

The situation improves rapidly when radial velocity measurements are available for both components (Fig. 1). In this case, it becomes possible to figure out the spectroscopic mass ratio and distance of the components, which serve as a scaling factor for the radii of each component. The combination of photometric and spectroscopic datasets leads to the determination of absolute eclipsing binary parameters in physical units, including masses, sizes, and luminosities of both components as well as distance from Earth. In this process, we can also calculate the atmosphere model and corresponding parameters (see e.g. [60–65]).

Some of aforementioned codes coupling light curve and radial velocity solutions are also capable to process additional kinds of parameters like timings of minima, interferometric measurements, and so on.

[9] http://phoebe-project.org.

[10] http://www.astro.keele.ac.uk/jkt/codes/jktebop.html.

[11] https://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html.

[12] http://caleb.eastern.edu/.

[13] http://www.astro.keele.ac.uk/jkt/debcat/.

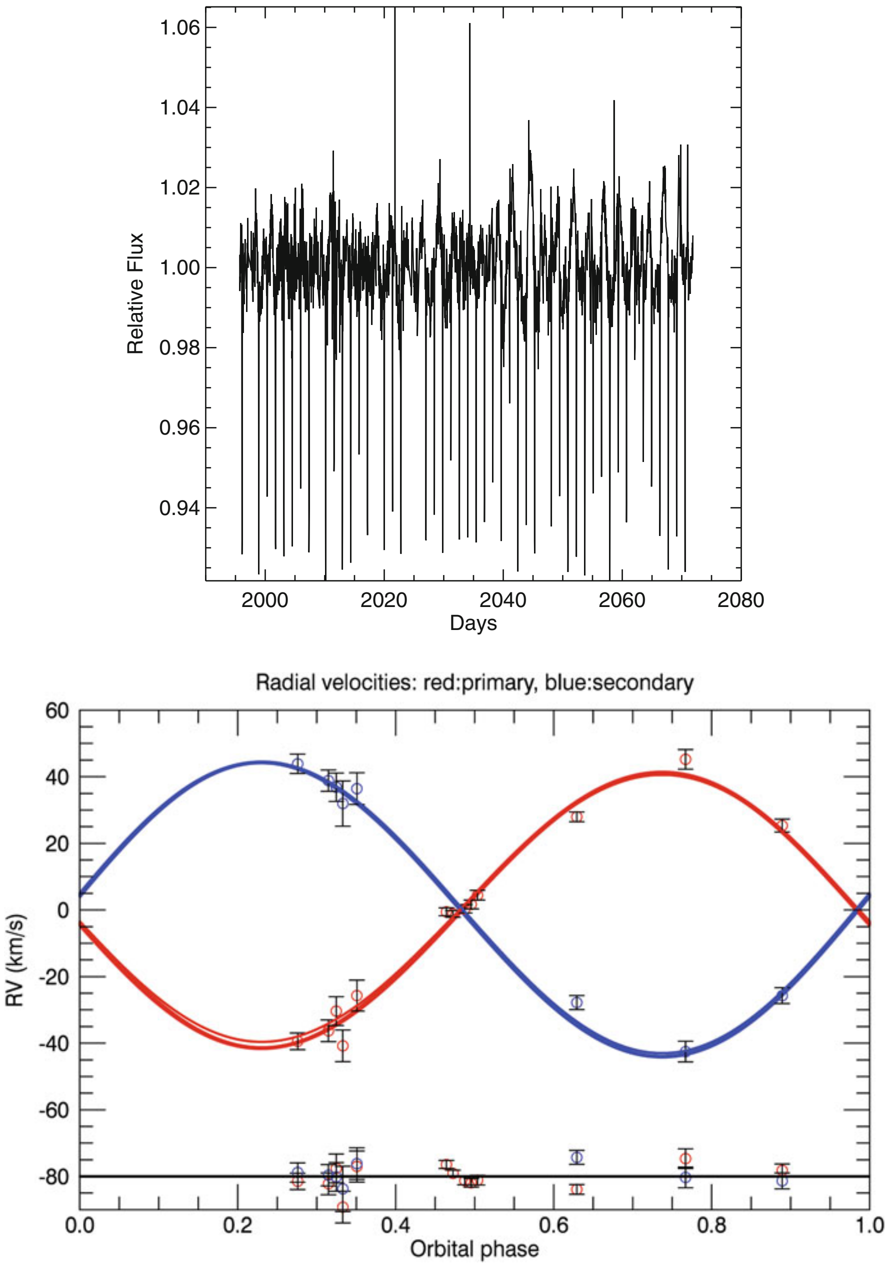

Fig. 1 *Top: Kepler* light-curve for USco J16163068−2512201 (= EPIC 203710387) over the full ∼76 days of the *K2* campaign two in Upper Scorpius. *Bottom:* Radial velocity measurements as a function of phase for the primary (blue symbols) and the secondary (red symbols) of USco J16163068−2512201. Figure taken from [56]

2 Review of EBs in Star-Forming Regions

The first low-mass EBs discovered in star-forming regions were identified in dedicated long-term photometric surveys monitoring the Orion region [66–68], one of the best studied area in the sky [69–74]. The first pair of eclipsing brown dwarfs (2MASS0535−05) at an age of about 1 Myr was reported by Stassun et al. [66] with a period of about 10 days, an eccentric orbit, a significant mass ratio characterised by complementary high-resolution spectroscopy [67]. Above the hydrogen-burning limit, there two pairs of low-mass stars reported in the Orion Nebula Cluster. JW 380 (= 2MASS J05351214−0531388) was identified in the Monitor project [68] with masses of 0.26 and 0.15 $M_{\odot}$ and in a period of 5.3 days. Par 1802 (= 2MASS J05351114−0536512) was identified independently by several team. It is a pair of M4 twins with a mass of 0.4 $M_{\odot}$, a period just under 5 days and non-zero eccentricity. Despite similar masses, both components exhibit distinct temperatures and luminosities, suggesting that newborn binaries may differ in the physical properties as a result of their formation [75–77]. In the ONC, we should add ISOY J0535−0447 announced by Morales-Calderón et al. [78] whose masses are estimated rather than measured because they fixed the semi-major axis. The primary is a K0 dwarf with a mass of 0.83 $M_{\odot}$ and a temperature of 5150 K while the secondary is most likely sub-stellar (0.05 $M_{\odot}$) but none have independent radius measurements because the lines are not resolved spectroscopically. These systems are key to test predictions from the theoretical pre-main-sequence models.

The advent of the *K2* mission after the loss of one gyroscope of the *Kepler* satellite [20] led to the discovery of a handful of EBs over a wide range of masses in the nearest OB association to the Sun, Upper Scorpius (USco). USco is located at 145 pc from the Sun and its age is currently debated in the literature, ranging between 5 and 10 Myr [79–86] and subject to numerous photometric and spectroscopic surveys [87–89]. The first one in the M dwarf regime, UScoCTIO 5 (2MASS J15595051−1944374), was selected as a photometric member by Ardila et al. [90] later resolved as a spectroscopic binary by Reiners et al. [91], and fully characterised by Kraus et al. [92] combining light curve from the photometry and high-resolution spectroscopy. A couple of other low-mass M dwarf EBs with EPIC numbers have been identified in the *K2* light curves [56, 86, 93] as well as the first brown dwarf (RIK72 = 2MASS J16033922−1851297) orbiting a low-mass dwarf [86]. A few other higher mass EBs have been reported at the age of USco but are not included in this review because we focus on the lowest mass objects [86, 93, 94]. Nonetheless, we should emphasise that the EB sequence of USco is fairly well constrained from high-mass stars down to the sub-stellar regime thanks to the exquisite light curve delivered by *K2* [86].

At very young ages, we should also mention the discovery of the low-mass, pre-main sequence eclipsing binary, CoRoT 223992193 (= 2MASS J06414422+0925024), whose secondary lies at the K/M border with a mass just under 0.5 $M_{\odot}$ and K dwarf primary with 0.67 $M_{\odot}$. This object belongs to the 3–6 Myr-old star-forming region NGC 2264 that was monitored continuously for 23.4 days by the CoRoT mission.

3 Review of EBs in Open Clusters

We can divide the stellar clusters targeted by *K2* into two groups: the intermediate-age clusters (100–200 Myr) whose main reference is the Pleiades with an age of 125±10 Myr [95–100] and the older more evolved open clusters like the Hyades (625±50 Myr) [101–108] and Praesepe (590–900 Myr) [99, 100, 102, 106, 109–112]. All these clusters are within 200 pc [113] and have metallicities close to solar or slightly super-solar [114–116].

In the Pleiades, HII 2407 known as a single-lined EB was identified eclipsing every 7.05 days [117]. The primary is well characterised with a spectral type of K1-K3, an effective temperature of 4970±95 K, a mass of 0.81±0.08 $M_{\odot}$, and a radius of 0.77±0.13 $R_{\odot}$. The secondary is a low-mass M dwarf, undetected in high-resolution spectra shortwards of 800 nm, yielding mass and radius estimates of 0.18 $M_{\odot}$ and 0.21 $R_{\odot}$, respectively. Another two EBs members of the Pleiades have been characterised photometrically and spectroscopically: HCG 76 and MHO 9 [118]. Both systems have long orbital periods with masses and radii well determined from the *K2* light curve and multiple radial velocity epochs. Two other higher mass EBs are presented in [118] as well as a possible member but not discussed in this review focusing on low-mass dwarfs. Finally, we highlight the possibility of MHO 9 being a hierarchical triple system due to its position above the Pleiades sequence in the H-R diagram (Fig. 2).

A pair of M dwarfs (2MASS J04463285+1901432) with a short period (∼0.62 days) was reported by Hebb et al. [119] with masses of 0.47±0.05 and 0.19±0.02 $M_{\odot}$ in the 150 Myr-old cluster NGC 1647 [120] located at 540 pc from the Sun [121]. The system is confirmed as a photometric and spectroscopic member with a radial velocity consistent with the mean value of the cluster. This new low-mass system represent an important link between the Pleiades and older clusters discussed below.

Four low-mass EBs have been revealed in the Praesepe cluster. PTFEB132.707+19.810 was announced by Kraus et al. [122] as a pair of 0.38+0.20 $M_{\odot}$ going around each other every 6 days and independently announced by Gillen et al. [123] as AD 3814. Another three EBs were included in the sample of low-mass EBs discussed in [123]. Two of these cluster candidates were classified as Praesepe members by four of six surveys [124–129], while the fourth one (AD 1508) is only labelled as member in two of these surveys. AD 2615 is a pair of almost equal-mass M dwarfs (0.21+0.25 $M_{\odot}$) with a period of 11.6 days and no eccentricity. The most special system, AD 3116, is composed of a M dwarf (∼0.28 $M_{\odot}$) and a brown dwarf with an estimated mass of 0.052 $M_{\odot}$. The period of this system is quite short, around 2 days, and this is the only system with an significant eccentricity of 0.142. The last system, with a doubtful membership, is composed of two low-mass dwarfs close to

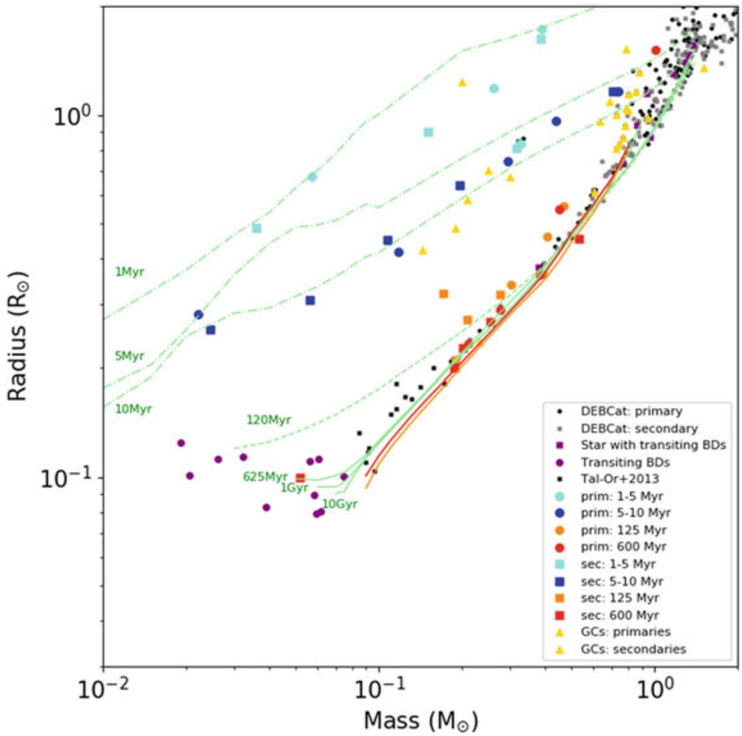

Fig. 2 Mass-radius relation for low-mass and sub-stellar eclipsing binaries in star-forming regions, open clusters, and globular clusters. The primaries and secondaries are plotted as dots and squares, respectively. Colour scheme as follows: 1–5 Myr (cyan), 5–10 Myr (blue); 125 Myr (orange); 600 Myr (red); globular clusters (yellow). The primaries and secondaries of EBs from the DEBcat database whose accuracies are better than 2% on their masses and radii are displayed as black and grey symbols. Overplotted with green lines are the BT-Settl isochrones for ages of 1 Myr, 5 Myr, 10 Myr, 120 Myr, 625 Myr, 1 Gyr, and 10 Gyr. We added the 5 Gyr-old low-metallicity tracks at [M/H] = −2.0 and −1.0 dex as orange and red lines, respectively

the 0.5 $M_{\odot}$, limit set in this review, revolving every 1.55 days. For a complete census of eclipsing systems in the Beehive cluster, we should highlight the seven transiting exoplanets, including three orbiting members with masses equal or below 0.5 $M_{\odot}$ [130]. These four system are unambiguously confirmed as astrometric members of the Praesepe cluster from the 3D kinematic selection using the second release of *Gaia* [100].

In the Hyades, no low-mass EB was disclosed in the *K2* light curves. However, one transiting system member of the Hyades [131, 132] was announced independently by David et al. [118] and Mann et al. [133]. The primary, vA 50, has a Neptune-size planet with an upper limit on its mass of 1.1 Jupiter mass based on high-resolution spectroscopic radial velocity with an accuracy of around 0.3 km s^{-1}. This planet is orbiting a M dwarf member of the Hyades with a mass of 0.26 $M_{\odot}$ and a radius of 0.32 $R_\odot$ every ∼3.5 days. This object is confirmed as a *Gaia* astrometric member located at 4.63 pc from the center of the Hyades cluster in 3D space [134].

4 Review of EBs in Globular Clusters

The globular clusters of our Milky Way are the oldest objects we know of. They are very massive containing up to a million of individual stars. There are two distinct populations of globular clusters, namely the classical population in the Galactic Halo [135] and the one in the Galactic Bulge [136]. The latter is younger (ages about 10 Gyr) and more metal-rich ($-0.7 <$ [Fe/H] $< +0.5$ dex) than the one in the Galactic Bulge [137]. The H-R diagram for a typical globular cluster looks very different than that of an open cluster. There are no main-sequence stars of spectral types earlier than F, but there are many red giants and other objects of the late evolutionary phase (for example the horizontal branch) of low-mass stars.

Since the first discovery of different internal populations (of the main-sequence as well as the giant branches) of stars in globular clusters [138] using the *Hubble Space Telescope*, this characteristic was found for almost all known aggregates. However, there are no unique pattern or correlation with other astrophysical parameters known so far. The only possible explanation of the observations is a different (enriched) helium abundance of these internal populations [139]. However, the evolutionary mechanism behind this enrichment of helium is still unknown.

From an observational point of view, globular clusters are difficult to observe because they are very dense (up to 100 stars per arcsec^2), typically far away (several kpc) from the Sun, and the low-mass members have apparent magnitudes fainter than 20th magnitude. In order to resolve most of the cluster areas, large ground-based telescope and good seeing conditions or satellite measurements are needed. Especially time-series of radial velocity measurements are almost not available.

In a series of papers, the Clusters Ages Experiment (CASE; [140, 141]) investigated photometrically and spectroscopically several eclipsing binary systems in different globular clusters. Most of these systems are so-called blue stragglers which are more luminous and bluer than stars at the main-sequence turnoff point for their host cluster [142]. Therefore, these objects are the brightest main-sequence stars in the cluster and easier to observe. However, these eclipsing binary systems are peculiar in the sense that normally a significant interaction between the components took place. For example, there is a scenario in which the primary component is reborn from a former white dwarf that accreted a new envelope through mass transfer from its companion. The secondary star has lost most of its envelope while starting its ascent onto the sub-giant branch. It failed to ignite helium in its core and is currently powered by an hydrogen-burning shell [140]. The time scales of the different stages of all these processes are not known. Analysing the individual components in the mass versus radius diagram (Fig. 1) might help putting further constraints on the models.

The estimation of the binary fraction of globular cluster members is severely influenced by the above described observational constraints. Sollima et al. [143] investigated the fraction of binary systems in a sample of 13 low-density Galactic globular clusters using Hubble Space Telescope observations. They analysed the colour distribution of main-sequence stars to derive the minimum fraction of binary systems required to reproduce the observed colour-magnitude diagram morphologies. They found that all the analysed globular clusters contain a minimum binary fraction larger than 6% within the core radius. However, the estimated global fractions of binary systems range from 10 to 50% depending on the cluster. More recently, [144] determined the binary fractions for 35 globular clusters using different models including a star superposition effect. They derived a binary fraction of 6.8–10.8% depending on the assumed shape to the binary mass-ratio distribution, with the best fit occurring for a binary distribution that favours low mass ratios (and higher binary fractions). Later on, [145] presented a long-time observational campaign using FLAMES spectra of 968 red giant branch stars located around the half-light radii in a sample of ten Galactic globular clusters. From these only 21 radial velocity variables were identified as bona-fide binary stars, yielding a binary fraction of $2.2 \pm 0.5\%$. Finally, [146] found a binary fraction between 3 and 38% depending on the regions of eight globular clusters. This short overview shows already the wide range of derived values and the need for a new homogeneous analysis of all available photometric and spectroscopic data.

The newest version (November 2017) of the variable stars in Galactic globular clusters catalogue [147] was used to estimate the percentage of eclipsing binary systems in respect to all known variables. Here, we want to recall that in these old aggregates, we find mainly pulsating variables, such as Cepheids, Giants, SX Phoenicis, RR Lyrae, and RV Tauri stars. The pulsational characteristics (i.e. periods as well as amplitudes) and astrophysical driving mechanism are widely different [148]. Nevertheless, the amplitudes of these stars are comparable to those of eclipsing binaries which should not introduce a significant bias in the detection rate. The mentioned catalogue includes 5604 stars in 151 globular clusters. In total, 399 eclipsing binaries of all types (excluding field stars) are listed. The distribution of the apparent magnitudes ranges from 12 to 24 with a peak at 17.5 mag, respectively. To put this number in a broader context, we need an estimate of the total number of investigated stars per cluster and thus the overall variability ratio. This number crucially depends on the telescope used, time series characteristics, and the methods applied to analyse time series. To get a rough estimate of this number, we use five recent publications. In the following, we list the total number of observed stars, the included variable stars (known, new, and suspected), and the eclipsing binaries: 7630/40/1 [149]; 4274/59/0 [150]; 132457/359/30 [151], 31762/47/1 [152]; and 11358/13/1 [153]. The number of detected variables in globular clusters is only a few percent from which only a maximum of 10% are eclipsing binaries. Therefore, also in the future the number of known eclipsing binary systems will not significantly increase. To identify possible eclipsing binary systems with low-mass companions, available light curves have to be analysed and the best candidates for spectroscopic follow-up observations selected.

5 Discussion

5.1 Frequency of EBs

Most of the low-mass EBs identified so far in star-forming regions and open clusters come from the *CoRoT* and *Kepler* space missions, except for those members of Orion. Here in this section we provide a tentative estimate of the frequency of low-mass EBs in the regions investigated so far to spot any potential trend with age or environment.

Several studies looked at the fraction of spectroscopic binaries in the M dwarf regime. The first study f detected variables in globular clusters is only a few percent from which only a maximum of 10% are eclipsing binaries. Therefore, also in the future the number of known eclipsing binary systems will not significantly increase. To identify possible eclipsing binary systems with low-mass companions, available light curves have to be analysed and the best candidates for spectroscopic follow-up observations selected.

of M dwarf multiples revealed about 1.8±1.8% of spectroscopic binaries (0.04−0.4 au) for a small sample of a few tens of low-mass stars [154]. The CARMENES team identified nine double-line spectroscopic binaries with periods in the 1.13−8000 days interval among their sample of 342 M dwarfs, yielding a multiplicity of 2.6% [155]. The search for spectroscopic binaries in the Sloan database returned 3−4% of multiple systems with separations less than 0.4 au with a possible towards the hottest M dwarfs [156]. At later spectral types, the frequency of spectroscopic binaries among late-M dwarf (M5−M8) binaries is around 11% for separations in the 0−6 au range [157], while an independent survey of 58 M8−L6 dwarfs yielded a 0.9−11.1% multiplicity at separations closer than 1 au [158]. Lastly, we should mention the statistical occurrence of M dwarf systems in the *Kepler* field of view of 7−13% based on the fractional incidence of low-mass eclipsing binaries [159].

While the *Kepler* mission monitored a single field towards the Cygnus constellation, the *K2* mission targeted star-forming regions and open clusters in the ecliptic for periods of approximately consecutive 80 days, corresponding to semi-major axis less than a = 0.36 au. However, if we assume that a minimum of two transits are necessary to identify any eclipsing binaries with high confidence, searches in *K2* would be sensitive to periods less than about 50 days, i.e. a ≤ 0.25 au (Fig. 3).

The census of low-mass EBs in Upper Scorpius, the Pleiades, Praesepe, NGC 2264, and Ruprecht 147 is 6, 2, 5, 1, and 2, respectively. These numbers represent lower limits for several reasons intrinsic to the search for eclipsing systems: incompleteness of the samples, inhomogeneous quality of the light-curves depending on the brightness of the targets, lack of sensitivity to large mass ratios, etc. The rotation properties of M dwarf members of Upper Scorpius, the Pleiades, and Praesepe have been investigated in great details [160–163] thanks to *K2*. Using a crude selection of potential M dwarfs with effective temperature below 3800 K and $V - K_s$ colours redder than 3.8 mag, we identified 867, 566, 619 low-mass

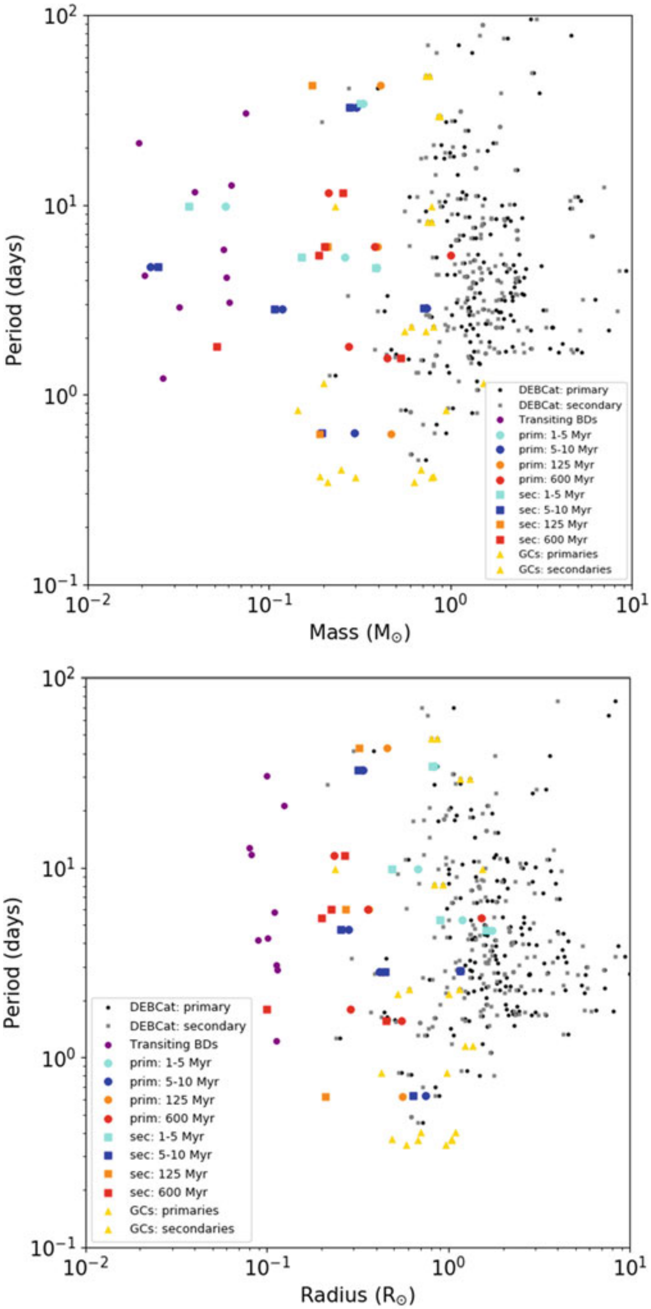

Fig. 3 The mass-period and radius-period diagrams of low-mass EBs: the primaries and secondaries are plotted as dots and squares, respectively. Colour scheme as follows: 1–5 Myr (cyan), 5–10 Myr (blue); 125 Myr (orange); 600 Myr (red), globular clusters (yellow), field EBs from the DEBcat database (black+grey)

members in Upper Scorpius, the Pleiades, Praesepe, respectively. We derived a frequency of EBs with semi-major axis less than ∼0.25 au of 0.64%, 0.35%, and 0.8% in these three regions. We estimate uncertainties up to 50% because of the low number statistics of published EBs, the rough photometric selection of M dwarf members, and the level of contamination of ground-based surveys before the advent of *Gaia*. Overall, we can argue that the frequency of EBs in clusters is below 1% for separations less than 0.25 au with no significant variation with age or environment. We also show the mass-semi-major axis and mass-eccentricity diagrams for cluster EBs in Fig. 4.

Finally, we should mention that only one brown dwarf pair is known eclipsing [66, 164], making any estimate of the frequency of sub-stellar EBs in young regions unreliable statistically. However, these types of systems should be rare although we cannot discard observational biases due to their intrinsic faintness and the lack of long-term monitoring sensitive to the sub-stellar population in star-forming regions and open clusters.

5.2 The Impact of Age on Mass and Radius

Figure 2 clearly shows that age has a strong impact on the radius of M dwarfs younger than ∼500 Myr: the younger the M dwarf, the larger is its radius, as predicted by evolutionary models [165–167]. At a given mass, the radius of a Pleiades M dwarf at 120 Myr is about 10% larger than the radius of a Praesepe or a Hyades member (600−700 Myr), which is comparable to the ones of older field stars (ages > 1 Gyr). We do not see any difference at ages older than 500 Myr for low-mass M dwarfs in the H-R diagram. Models do predict differences in the sub-stellar regime but only one brown dwarf with an age larger than 500 Myr has been reported in Praesepe. The difference is small going from 600 to 120 Myr but significant moving towards much younger ages: the radius of a 0.25 $M_{\odot}$ is approximately 3 and 5 times larger at 5−10 and ∼3 Myr, respectively. We observe a clear difference in radii of M dwarf members of Upper Scorpius (5−10 Myr; blue symbols) with those in Orion (<3 Myr; cyan) compared to those of the Pleiades (125 Myr; orange symbols). We note that one EB system identified in NGC2264 [168] confirms that the age of the cluster lies between the age of Orion and Upper Scorpius based on its location in the H-R diagram displayed in Fig. 2. We also remark that the system found in NGC 1647 [119] whose age is constrained to 150±10 Myr lies slightly above the evolutionary model at 120 Myr (Pleiades-like age), suggesting that a revision of the age of NGC 1647 (and possibly its distance checking the parallaxes of *Gaia* DR2) might be needed.

We also investigated the dispersion of the 11 eclipsing brown dwarfs (purple dots in Fig. 2) revealed by several missions and ground-based surveys. This dispersion might be the consequence of tides from the primary star yielding engulfment of the companions, magnetic activity, presence of cold spots on the surface of the brown dwarf, irradiation from the host star, and/or metallicity. The puzzle remains,

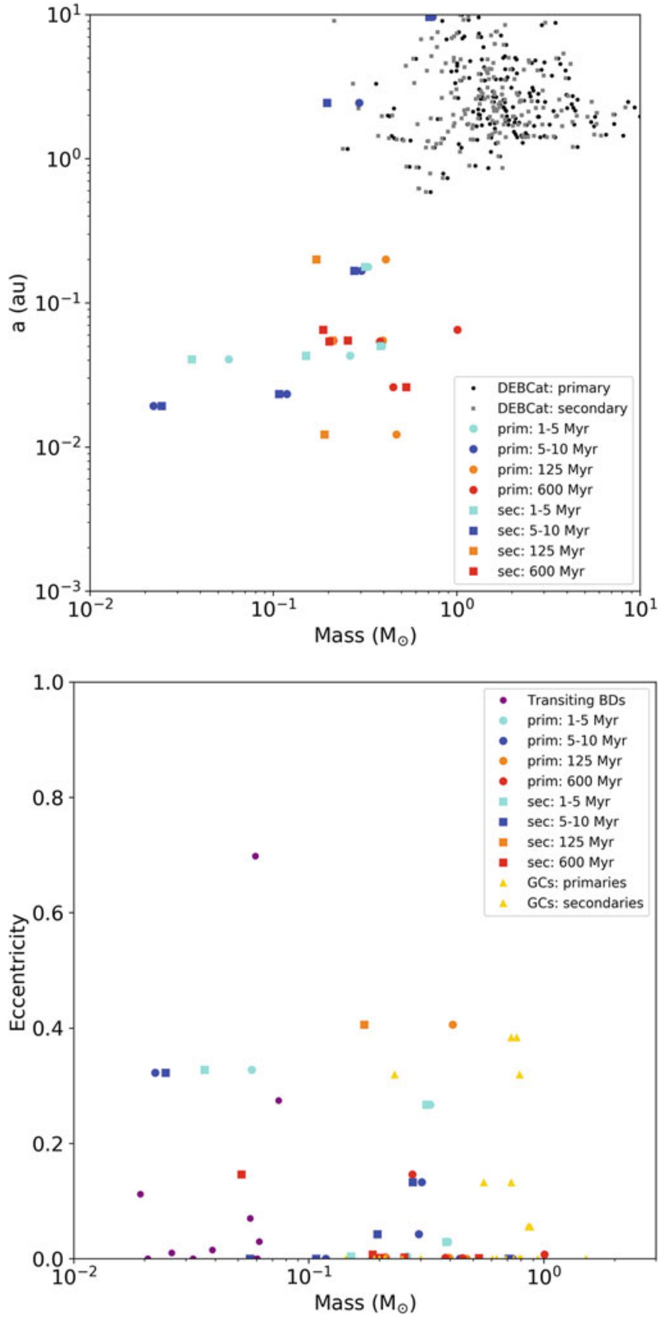

Fig. 4 The mass-semi-major axis and mass-eccentricity diagrams of low-mass EBs in star-forming regions and clusters. The primaries and secondaries are plotted as dots and squares, respectively. Colour scheme as follows: 1–5 Myr (cyan), 5–10 Myr (blue); 125 Myr (orange); 600 Myr (red), globular clusters (yellow), field EBs from the DEBcat database (black+grey)

however, under debate. Because of the improved knowledge on the impact of the age on the radius of M dwarfs and brown dwarfs gathered over the past years mainly thanks to *Kepler K2*, we collected information on the ages of the primary stars from the discovery papers to compare the values with the inferred from the latest BT-Settl isochrones [167]. We considered the effect of age in this review keeping in mind current uncertainties on the mass determinations of the sub-stellar companions arising from the uncertainties on the mass of the primary and the grazing transits of some of the examples.

First of all, we note that two of these brown dwarfs orbit a M dwarf primary. Based on the above discussion, we can argue that the ages of these M dwarfs are older than 100 Myr although any older age is possible when taking into account the uncertainties on their masses and radii. Comparing the positions of the eclipsing brown dwarfs to the latest BT-Settl isochrones, we divided the sample into several groups. Two systems (KOI-415 and LHS 6343) appear very old, older than the others due to their small radii, consistent with the analysis of the discovery papers. We note again the low metallicity of KOI-415 ([Fe/H] = −0.24 dex) suggesting an old age. Another three systems (WASP-30, KOI-189, KOI-205) appear old, with ages around 1 Gyr or older [169–171]. The positions of CoRoT-15b and CoRoT-33b in the H-R diagram fit well the 300 Myr-old isochrone. However, we caution this point because the masses of the secondaries are ill-defined due to the intrinsic faintness of CoRoT-15 ($V \sim 16$ mag) and the grazing eclipse of CoRoT-33b [172, 173]. Nonetheless, those two systems appear as intermediate age-wise between the aforementioned systems and the (possibly) youngest ones described below. The last group of brown dwarfs exhibit inflated radii with respect to their siblings, the most extreme one being Kepler-39b [174]. Its age remains controversial depending on the method used for its determination: fit to the spectrum of the solar-type primary suggests 1.0−2.9 Gyr while the gyrochronology age infers 0.4−1.6 Gyr [175]. The brown dwarf is best fit by isochrones with ages between 50 and 120 Myr. The masses and radii of the brown dwarfs in the other systems (NLTT 41135, KELT-1b, and CoRoT-3b) are best fit by isochrones with ages bracketed by the Pleiades and Hyades isochrones [174, 176, 177]. We emphasise that three of the solar-type primaries appear over-luminous compared to the others and the BT-Settl isochrones. Overall, in spite of the current uncertainties on the masses and radii of the sub-stellar secondaries, we cannot discard age to have a significant effect on their radii due to the dependence of physical properties of brown dwarfs with gravity [178–182]. The revision of the distances of the host stars with the *Gaia* parallaxes should revise some of these discrepancies and decrease current error bars.

5.3 The Impact of Metallicity on Mass and Radius

It is widely established that the fraction of stars hosting planets is larger with higher metallicity. The average metallicity of a volume-limited sample of stars with planets that have been specifically searched for planets peaks at [Fe/H] $\sim +0.1$ [183, 184].

The frequency of metal-poor stars with planets is of the order of 5% or less, while more than 30% of metal-rich stars ($\geq +0.25$ dex) host planets. Moreover, there might be a trend towards low-mass planets with short periods orbiting low metallicity stars [185, 186].

We should compare the different frequencies and see whether metallicity has an impact [187].

The spectra of M dwarfs start to be affected by the dearth of metals at optical and near-infrared wavelengths for metallicities below [Fe/H] ~ -0.5 dex [188–191], trend extending towards at temperatures below 2500 K [192, 193]. The impact of metallicity on the sample of low-mass EBs in star-forming regions and open clusters is hard to disentangle from the effect of age because all regions have a metallicity equal or close to solar within 0.2 dex.

We also looked at the possible impact of metallicity on the dispersion of eclipsing brown dwarfs in the H-R diagram (Fig. 2). Among this sample, only two stars stand out due to their metallicity: CoRoT-33 a G9V with [Fe/H] = $+0.44 \pm 0.10$ dex [173] and KOI-415 a G0IV metal-poor solar-type analogue with [Fe/H] = -0.24 ± 0.10 dex [194]. The latter is not so different from the bulk of stars with eclipsing sub-stellar companions because the difference in metallicity is less 0.2 dex but we note that its orbit is eccentric and its radius among the two lowest. CoRoT-33 is classified as a old star with an age greater than 4.6 Gyr based on a serie of indicators [173]. The radius of the brown dwarf is 40% larger than KOI-415 for an almost identical mass (59 M_{Jup} vs. 62 M_{Jup}). Based on this comparison, we conclude that metallicity may indeed play a role in the properties of sub-stellar objects, in line with the spectral differences seen in L and T subdwarfs [192, 193].

5.4 The Role of Stellar Activity and Activity Cycles

The 11 year-long activity cycle on the Sun is known for a long time. The first long-term brightness changes which were interpreted as starspot cycles for M-type stars were reported by Phillips and Hartmann [195]. Chromospheric activity of F- to M-type stars can be studied using long-term Ca H&K data, for example from the Mount Wilson survey [196]. Those observations show cyclic variations yielding relations between the rotational period, the length of the activity cycle, and other stellar properties. Most important, faster rotating stars have shorter activity cycles [197], which can be explained by the classical dynamo theory. The square of the ratio of the cycle length and the rotational period can be used as a quantity to parametrise activity cycles.

In many active stars the starspots are so large that they cause brightness variations which can be few tens of percent from the mean light level [198], thus making them easily observable. The observed cycle lengths seem to converge with stellar age from a maximum dispersion around the Pleiades' age towards the solar cycle value at the Sun's age [199], and that the overall short- and long-term photometric variability increases with inverse Rossby number. The cycles of active stars are often not as regular and cyclic as their more quiet counterparts. Many active stars exhibit multiple cycle lengths simultaneously and cycle lengths in active stars are also often variable [200]. Most intriguing is the so-called flip-flop phenomenon where the activity concentrates on two permanent active longitudes, and flips between the two every few years [201].

The phenomenon are also important for the interpretation of light curves for eclipsing binary systems. The chromospherically active components of 180 low-mass pre-main sequence stars and chromospherically active binary systems have been looked at by Parihar et al. [202] and Eker et al. [203], respectively. The light curves of such systems are complicated to interpret if one or even two components show spots on different time scales and with different intensities. The effects of starspots on the light curves of eclipsing binaries, and, in particular, how they may affect the accurate measurement of eclipse timings have been investigated by Watson and Dhillon [204]. For systems containing a low-mass main-sequence star and a white dwarf, the times of primary eclipse ingress and egress can be altered by several seconds (larger effect for lower inclinations) for typical binary parameters and star-spot depressions. These effects cause a jitter in the residuals of O−C diagrams, which can also result in the false detection of spurious orbital period changes.

A nice example of how to model a light curve taking account of all the above mentioned effects is presented by Czesla et al. [205], who investigated the short-period (2.17 d) eclipsing binary CoRoT 105895502. They found a starspot with a period of about 40 days which remains quasi-stationary in the binary frame, and one starspot showing prograde motion at a rate of 2.3 degree per day, whose lifetime exceeds the duration of the observation (145 days). Only with eclipsing binary systems it is possible to study the complex correlations between chromospheric activity, spot cycles, and the astrophysical parameters in more details.

5.5 Flares in M Dwarfs

Flares are mostly rapid transients lasting of the order of minutes or dozens of minutes, which are observable in different regions of the electromagnetic spectrum, from the ultra-violet to the X-ray domains. They are often observed on M dwarfs because they ideally fulfill the necessary conditions. Firstly, they are low mass stars with magnetic fields that remain active for a substantial part of their lives, and, secondly, the large difference between hot flaring regions and the cool photosphere give a higher chance of magnetic field generation. The energy of flares on M dwarfs can reach 10^{28}–10^{29} W. For example, on 2014 April 23, the *SWIFT* satellite detected a super-flare from the nearby young M-type binary DG CVn with the radiated energy about 4–9×10^{28} W of energy in the 0.3–10 keV X-ray bandpass. This is about 10,000 times stronger than the most powerful solar flare on record [206]. The current available large surveys like ASAS-SN, Next Generation Transient Survey (NGTS), *Kepler/K2*, and *TESS* provide excellent photometric data to study the occurrence and

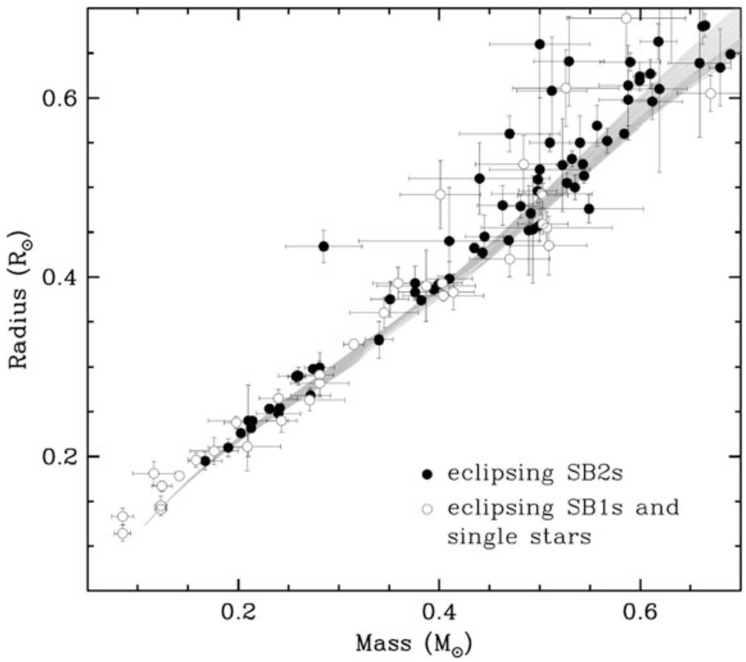

Fig. 5 Mass-radius diagram for low-mass stars, including all measurements for double-lined eclipsing binaries (SB2; filled symbols) as well as determinations for single-lined eclipsing systems (SB1) and single stars (open symbols). Solar-metallicity Dartmouth isochrones are shown for comparison, for ages ranging from 1 to 13 Gyr (grey band) [219]

frequency of flares on M dwarfs (e.g. [207–213]). Furthermore, selected M dwarfs with observed flares were also monitored spectroscopically [214] to determine their ages and study the influence of the flare on the presence of possible exoplanets orbiting M dwarfs.

It was proposed that flares together with dark magnetic spots are responsible for the difference between the observed radii of M dwarfs and predicted theoretical values from evolutionary models. This discrepancy could be 5–10% or even more, depending on the model. Up to the beginning of the twenty-first century, only a few low-mass binary systems with M dwarf companions had measured radii with sufficient accuracy for modelling: CM Dra [215], YY Gem [216], CU Cnc [217], and GU Boo [218]. The situation in 2013 is reviewed in [219], see citations therein and Fig. 5). New solutions using more accurate photometric and spectroscopic observations as well as improved models decreased the discrepancy up to 2–3% for CM Dra [220]. The remaining difference could be caused by uncertain He abundance, for example. The calculation made for CM Dra showed that increasing the He abundance by 7% solves the remaining discrepancy in radii [220].

6 Future Prospects for EBs in Clusters

The numbers of photometric light curves and transiting systems available in star-forming regions and open clusters has been overwhelming thanks to the *CoRoT* mission and the (unexpected) advent of the *K2* mission focusing on the ecliptic. The future looks very bright too, with the 2-year Transiting Exoplanet Survey Satellite (*TESS*) mission [221][14] currently in space that will fully cover both the southern and northern hemispheres with a cadence of 30 min. The PLAnetary Transits and Oscillations of stars (*PLATO*) mission [222][15] is planned for a launch in 2026 aiming at targeting one million stars with two major objectives: the discovery of transiting Earth-like planets in the habitable zone of their host star and the study of stellar oscillations. However, *TESS* and *PLATO* might not contribute too much to the study of low-mass M dwarf members of star-forming regions and open clusters because they tend to avoid the ecliptic due to confusion issues and will focus on stars brighter than *K2*. We encourage the *PLATO* community to design a specific program focusing on a few clusters bracketing a large age range for several days to further constrain planetary and stellar evolutionary models.

The Young Exoplanet Transit Initiative (YETI) is an independent large ground-based involving multi-site telescopes and instruments designed to focus on nearby young regions to look for planetary transits [25]. Only one transiting planetary candidate (CVSO 30) has been identified but not yet unambiguously confirmed so far [223]. As a spin-off result, a few EBs have been discovered in several clusters, including the NGC 7243 (∼250 Myr; ∼700 pc) and Trumpler 37 (4 Myr; 840 pc) clusters [224, 225]. The main difficulties of ground-based photometric surveys lies in the length of the nights (8 h vs. 24 h for space missions) with weather dependent conditions, the limited numbers of dedicated nights (a few per week/month vs. 27/80 days for *TESS/K2*), and the low precision of single measurements (at best a few mmag vs. less than 1 mmag from space for the same brightness). As a consequence, transiting exoplanets are tough to identify in active young stars but low-mass EBs should be easier to spot even for masses below 0.6 $M_{\odot}$.

In Fig. 2, we can clearly see a gap in age between 10 and 120 Myr. We highlight some dedicated programs to fill up that gap to investigate the evolution of masses and radii with age and constrain state-of-the-art isochrones.

- First, we should focus on the nearest (<200 pc) open clusters in this age range. The options are limited, resulting only a few regions: IC 2391 [96], IC 2602 [226], IC 4665 [227], α Persei [228] and NGC 2451 [229] for which *Gaia* will provide soon revised membership lists with accurate kinematics. One of the main issue though is the extension of these clusters in the sky, typically larger than most optical and infrared detectors. To reach the low-mass M dwarfs in those regions, the infrared camera VIRCAM on the VISTA telescope [230, 231]

[14] https://heasarc.gsfc.nasa.gov/docs/tess/.

[15] http://sci.esa.int/plato/.

might be the best option is the photometric accuracy can be guaranteed over several nights or weeks to look for dipping events of a few tens of magnitudes in the lowest mass members. Another alternative consists in dedicated a month of observing time with the most sensitive cameras of planet-hunter surveys with a preference to the ones most sensitive to far-red (≥ 750 nm) and infrared wavelengths ($1-2\,\mu$m) like the Next-Generation Transit Survey (NGTS; [232]), the TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST; [233]), or the Search for habitable Planets EClipsing ULtra-cOOl Stars (SPECULOOS; [234]) rather than in the visible such as Trans-atlantic Exoplanet Survey (Tr-ES; [235]), Hungarian Automated Telescope Network (HATNet; [236]), the Wide Angle Search for Planets (WASP) North and South [237], the XO telescope [238], the Kilodegree Extremely Little Telescope (KELT; [239]).
- Secondly, members of young nearby moving groups younger than the Pleiades might represent ideal targets to look for exoplanets and EBs because they share the same age and metallicity[84, 179, 240–242]. Several moving groups and associations have been identified in the Solar neighbourhood (Ursa Major, TW Hya, β Pic, AB Doradus, η Chamaeleon, ϵ Chamaeleon, Tucana-Horologium) and hundreds of their members confirmed spectroscopically [241]. The main advantage is the closest distances of these members whose kinematics will be refined soon thanks to the releases of the *Gaia* astrometric datasets. One of the main drawback, as for all young stars, is the unknown levels of activity that might mimic the presence of planets. However, the large amplitude and RV modulation of low-mass EBs should be less affected to the intrinsic stellar activity.
- A third option is to search for low-mass companions of B- and A-type stars using X-ray data [243]. Known EBs can be located in a colour-magnitude diagram using *Gaia* data. Systems close to the zero-age-main-sequence can be easily identified because the contribution of a possible low-mass companion to the combined colour and absolute magnitude is negligible. The next steps consists in identifying those systems in the public X-ray catalogues such as *Chandra* [244], *ROSAT* [245], and *XMM-Newton* [246]. Normally, more massive stars have only weak X-ray fluxes compared to their low-mass counterparts [247]. From their spectrum and the amount of flux in X-rays, a first estimation of the astrophysical parameters of the companions can be done [248] to select systems for further spectroscopic studies.

Acknowledgements NL supported by the Spanish Ministry of Economy and Competitiveness (MINECO) under the grant AYA2015-69350-C3-2-P. This research has made use of the Simbad and Vizier databases, operated at the centre de Données Astronomiques de Strasbourg (CDS), of NASA's Astrophysics Data System Bibliographic Services (ADS), and the WEBDA database, operated at the Department of Theoretical Physics and Astrophysics of the Masaryk University.

References

1. T. Henry, O. Franz, L. Wasserman, G.F. Benedict, P. Shelus, P. Ianna, J.D. Kirkpatrick, D. McCarthy, Bull. Am. Astron. Soc. **29**, 1278 (1997)
2. J.G. Winters, T.J. Henry, J.C. Lurie, N.C. Hambly, W.C. Jao, J.L. Bartlett, M.R. Boyd, S.B. Dieterich, C.T. Finch, A.D. Hosey, P.A. Ianna, A.R. Riedel, K.J. Slatten, J.P. Subasavage, Astron. J. **149**, 5 (2015). https://doi.org/10.1088/0004-6256/149/1/5
3. S.S. Kumar, E.K.L. Upton, Astron. J. **68**, 76 (1963)
4. J.C. Tarter, Bull. Am. Astron. Soc. **8**, 517 (1976)
5. G. Chabrier, I. Baraffe, Annu. Rev. Astron. Astrophys. **38**, 337 (2000)
6. J. Southworth, P.F.L. Maxted, B. Smalley, Astron. Astrophys. **429**, 645 (2005). https://doi.org/10.1051/0004-6361:20041867
7. G. Torres, J. Andersen, A. Giménez, Annu. Rev. Astron. Astrophys. **18**, 67 (2010). https://doi.org/10.1007/s00159-009-0025-1
8. D.M. Popper, Annu. Rev. Astron. Astrophys. **18**, 115 (1980). https://doi.org/10.1146/annurev.aa.18.090180.000555
9. J. Andersen, Annu. Rev. Astron. Astrophys. **3**, 91 (1991). https://doi.org/10.1007/BF00873538
10. J. Southworth (2014). e-prints. arXiv:1411.1219
11. M.A. Svechnikov, E.L. Perevozkina, VizieR Online Data Cat. **5121**, 5 (2004)
12. I. Soszyński, A. Udalski, M.K. Szymański, Ł. Wyrzykowski, K. Ulaczyk, R. Poleski, P. Pietrukowicz, S. Kozłowski, D.M. Skowron, J. Skowron, P. Mróz, M. Pawlak, K. Rybicki, A. Jacyszyn-Dobrzeniecka, Acta Astron. **67**, 297 (2017). https://doi.org/10.32023/0001-5237/67.4.1
13. K.G. Hełminiak, M. Konacki, M. RóŻyczka, J. KałuŻny, M. Ratajczak, J. Borkowski, P. Sybilski, M.W. Muterspaugh, D.E. Reichart, K.M. Ivarsen, J.B. Haislip, J.A. Crain, A.C. Foster, M.C. Nysewander, A.P. LaCluyze, Mon. Not. R. Astron. Soc. **425**, 1245 (2012). https://doi.org/10.1111/j.1365-2966.2012.21510.x
14. L. Zhang, H. Lu, X.L. Han, L. Jiang, Z. Li, Y. Zhang, Y. Hou, Y. Wang, Z. Cao, New Astron. **61**, 36 (2018). https://doi.org/10.1016/j.newast.2017.11.007
15. C.H. Lee, C.C. Lin, Res. Astron. Astrophys. **17**, 15 (2017). https://doi.org/10.1088/1674-4527/17/2/15
16. A.J. Drake, S.G. Djorgovski, A. Mahabal, E. Beshore, S. Larson, M.J. Graham, R. Williams, E. Christensen, M. Catelan, A. Boattini, A. Gibbs, R. Hill, R. Kowalski, Astrophys. J. **696**, 870 (2009). https://doi.org/10.1088/0004-637X/696/1/870
17. A.A. Mahabal, S.G. Djorgovski, A.J. Drake, C. Donalek, M.J. Graham, R.D. Williams, Y. Chen, B. Moghaddam, M. Turmon, E. Beshore, S. Larson, Bull. Astron. Soc. India **39**, 387 (2011)
18. S.G. Djorgovski, A.A. Mahabal, C. Donalek, M.J. Graham, A.J. Drake, B. Moghaddam, M. Turmon, Flashes in a star stream: automated classification of astronomical transient events. e-Prints (2012). arXiv:1209.1681. https://ui.adsabs.harvard.edu/abs/2012arXiv1209.1681D
19. J.L. Tonry, L. Denneau, A.N. Heinze, B. Stalder, K.W. Smith, S.J. Smartt, C.W. Stubbs, H.J. Weiland, A. Rest, Publ. Astron. Soc. Pac. **130**(6), 064505 (2018). https://doi.org/10.1088/1538-3873/aabadf
20. W.J. Borucki, D. Koch, G. Basri, N. Batalha, T. Brown, D. Caldwell, J. Caldwell, J. Christensen-Dalsgaard, et al., Science **327**, 977 (2010). https://doi.org/10.1126/science.1185402
21. S.B. Howell, C. Sobeck, M. Haas, M. Still, T. Barclay, F. Mullally, J. Troeltzsch, S. Aigrain, S.T. Bryson, D. Caldwell, W.J. Chaplin, W.D. Cochran, D. Huber, G.W. Marcy, A. Miglio, J.R. Najita, M. Smith, J.D. Twicken, J.J. Fortney, Publ. Astron. Soc. Pac. **126**, 398 (2014). https://doi.org/10.1086/676406
22. A.M. Geller, R.D. Mathieu, H.C. Harris, R.D. McClure, Astron. J. **137**, 3743 (2009). https://doi.org/10.1088/0004-6256/137/4/3743

23. K.E. Milliman, R.D. Mathieu, A.M. Geller, N.M. Gosnell, S. Meibom, I. Platais, Astron. J. **148**, 38 (2014). https://doi.org/10.1088/0004-6256/148/2/38
24. E.M. Leiner, R.D. Mathieu, N.M. Gosnell, A.M. Geller, Astron. J. **150**, 10 (2015). https://doi.org/10.1088/0004-6256/150/1/10
25. R. Neuhäuser, R. Errmann, A. Berndt, G. Maciejewski, H. Takahashi, W.P. Chen, D.P. Dimitrov, T. Pribulla, E.H. Nikogossian, E.L.N. Jensen, L. Marschall, Z.Y. Wu, A. Kellerer, F.M. Walter, C. Briceño, R. Chini, M. Fernandez, S. Raetz, G. Torres, D.W. Latham, S.N. Quinn, A. Niedzielski, Ł. Bukowiecki, G. Nowak, T. Tomov, K. Tachihara, S.C.L. Hu, L.W. Hung, D.P. Kjurkchieva, V.S. Radeva, B.M. Mihov, L. Slavcheva-Mihova, I.N. Bozhinova, J. Budaj, M. Vaňko, E. Kundra, L'. Hambálek, V. Krushevska, T. Movsessian, H. Harutyunyan, J.J. Downes, J. Hernandez, V.H. Hoffmeister, D.H. Cohen, I. Abel, R. Ahmad, S. Chapman, S. Eckert, J. Goodman, A. Guerard, H.M. Kim, A. Koontharana, J. Sokol, J. Trinh, Y. Wang, X. Zhou, R. Redmer, U. Kramm, N. Nettelmann, M. Mugrauer, J. Schmidt, M. Moualla, C. Ginski, C. Marka, C. Adam, M. Seeliger, S. Baar, T. Roell, T.O.B. Schmidt, L. Trepl, T. Eisenbeiß, S. Fiedler, N. Tetzlaff, E. Schmidt, M.M. Hohle, M. Kitze, N. Chakrova, C. Gräfe, K. Schreyer, V.V. Hambaryan, C.H. Broeg, J. Koppenhoefer, A.K. Pandey, Astron. Nachr. **332**, 547 (2011). https://doi.org/10.1002/asna.201111573
26. A. Rau, S.R. Kulkarni, N.M. Law, J.S. Bloom, D. Ciardi, G.S. Djorgovski, D.B. Fox, A. Gal-Yam, C.C. Grillmair, M.M. Kasliwal, P.E. Nugent, E.O. Ofek, R.M. Quimby, W.T. Reach, M. Shara, L. Bildsten, S.B. Cenko, A.J. Drake, A.V. Filippenko, D.J. Helfand, G. Helou, D.A. Howell, D. Poznanski, M. Sullivan, Publ. Astron. Soc. Pac. **121**, 1334 (2009). https://doi.org/10.1086/605911
27. N.M. Law, S.R. Kulkarni, R.G. Dekany, E.O. Ofek, R.M. Quimby, P.E. Nugent, J. Surace, C.C. Grillmair, J.S. Bloom, M.M. Kasliwal, L. Bildsten, T. Brown, S.B. Cenko, D. Ciardi, E. Croner, S.G. Djorgovski, J. van Eyken, A.V. Filippenko, D.B. Fox, A. Gal-Yam, D. Hale, N. Hamam, G. Helou, J. Henning, D.A. Howell, J. Jacobsen, R. Laher, S. Mattingly, D. McKenna, A. Pickles, D. Poznanski, G. Rahmer, A. Rau, W. Rosing, M. Shara, R. Smith, D. Starr, M. Sullivan, V. Velur, R. Walters, J. Zolkower, Publ. Astron. Soc. Pac. **121**, 1395 (2009). https://doi.org/10.1086/648598
28. H.N. Russell, J.E. Merrill, *The Determination of the Elements of Eclipsing Binaries* (1952). https://ui.adsabs.harvard.edu/abs/1952deeb.book.....R
29. M.S. Zverev, B.V. Kukarkin, D.Ya. Martynov, P.P. Parenago, N.F. Florya, V.P. Tsesevich, *Variable Stars*, vol. III (1947). https://ui.adsabs.harvard.edu/abs/1947pezv.book.....Z
30. P.B. Etzel, in *Photometric and Spectroscopic Binary Systems* (1981), p. 111
31. E. Budding, Astrophys. Space Sci. **22**(1), 87 (1973). https://doi.org/10.1007/BF00642825
32. E. Budding, M. Zeilik, *Some Rapidly Rotating Cool Stars and Their Activity*, vol. 254 (1986), p. 290. https://doi.org/10.1007/3-540-16763-3_200
33. E. Budding, M. Zeilik, Astrophys. J. **319**, 827 (1987). https://doi.org/10.1086/165500
34. D.B. Wood, Astron. J. **76**, 701 (1971). https://doi.org/10.1086/111187
35. D.B. Wood, Technical Report X-110-72-473, Publications of the Goddard Space Flight Center, Greenbelt (1972)
36. D.B. Wood, Publ. Astron. Soc. Pac. **85**(504), 253 (1973). https://doi.org/10.1086/129447
37. G. Hill, *Publications of the Dominion Astrophysical Observatory Victoria*, vol. 15 (Queen's Printer, Ottawa, 1979), p. 298
38. G. Hill, S. Rucinski, IAU Comm. Close Binary Stars **21**, 135 (1993)
39. S.M. Ruciński, Acta Astron. **23**, 79 (1973)
40. S.M. Rucinski, Acta Astron. **24**, 119 (1974)
41. R.E. Wilson, E.J. Devinney, Astrophys. J. **166**, 605 (1971). https://doi.org/10.1086/150986
42. R.E. Wilson, E.J. Devinney, Astrophys. J. **171**, 413 (1972). https://doi.org/10.1086/151293
43. R.E. Wilson, Astrophys. J. **672**(1), 575 (2008). https://doi.org/10.1086/523634
44. R.E. Wilson, W. Van Hamme, Astrophys. J. **780**(2), 151 (2014). https://doi.org/10.1088/0004-637X/780/2/151
45. A. Prša, T. Zwitter, Astrophys. J. **628**(1), 426 (2005). https://doi.org/10.1086/430591

46. A. Prša, K.E. Conroy, M. Horvat, H. Pablo, A. Kochoska, S. Bloemen, J. Giammarco, K.M. Hambleton, P. Degroote, Astrophys. J. Suppl. Ser. **227**(2), 29 (2016). https://doi.org/10.3847/1538-4365/227/2/29
47. M. Horvat, K.E. Conroy, H. Pablo, K.M. Hambleton, A. Kochoska, J. Giammarco, A. Prša, Astrophys. J. Suppl. Ser. **237**(2), 26 (2018). https://doi.org/10.3847/1538-4365/aacd0f
48. A. Prša, *Modeling and Analysis of Eclipsing Binary Stars: The Theory and Design Principles of PHOEBE* (IOP Publishing, Bristol, 2018). https://doi.org/10.1088/978-0-7503-1287-5
49. J. Devor, Astrophys. J. **628**(1), 411 (2005). https://doi.org/10.1086/431170
50. J. Devor, D. Charbonneau, Astrophys. J. **653**(1), 647 (2006). https://doi.org/10.1086/508609
51. O. Tamuz, T. Mazeh, P. North, Mon. Not. R. Astron. Soc. **367**(4), 1521 (2006a). https://doi.org/10.1111/j.1365-2966.2006.10049.x
52. T. Mazeh, O. Tamuz, P. North, Mon. Not. R. Astron. Soc. **367**(4), 1531 (2006b). https://doi.org/10.1111/j.1365-2966.2006.10050.x
53. P. Hadrava, Publ. Astron. Inst. Czechoslov. Acad. Sci. **92**, 1 (2004)
54. T. Pribulla, in *From Interacting Binaries to Exoplanets: Essential Modeling Tools*, *IAU Symposium*, vol. 282, ed. by M.T. Richards, I. Hubeny (2012), pp. 279–282. https://doi.org/10.1017/S1743921311027566
55. D.H. Bradstreet, Soc. Astron. Sci. Annu. Symp. **24**, 23 (2005)
56. N. Lodieu, R. Alonso, R. González Hernández, J. I. Sanchis-Ojeda, N. Narita, Y. Kawashima, K. Kawauchi, A. Suárez Mascareño, H. Deeg, et al., Astron. Astrophys. **584**, A128 (2015). https://doi.org/10.1051/0004-6361/201527464
57. L'. Hambálek, T. Pribulla, Contrib. Astron. Observatory Skalnate Pleso **43**(1), 27 (2013)
58. D. Terrell, R.E. Wilson, Astrophys. Space Sci. **296**(1–4), 221 (2005). https://doi.org/10.1007/s10509-005-4449-4
59. W. van Hamme, Astron. J. **106**, 2096 (1993). https://doi.org/10.1086/116788
60. A. Claret, S. Bloemen, Astron. Astrophys. **529**, A75 (2011). https://doi.org/10.1051/0004-6361/201116451
61. A. Claret, P.H. Hauschildt, S. Witte, Astron. Astrophys. **546**, A14 (2012). https://doi.org/10.1051/0004-6361/201219849
62. A. Claret, P.H. Hauschildt, S. Witte, Astron. Astrophys. **552**, A16 (2013). https://doi.org/10.1051/0004-6361/201220942
63. A. Claret, Astron. Astrophys. **600**, A30 (2017). https://doi.org/10.1051/0004-6361/201629705
64. A. Claret, Astron. Astrophys. **618**, A20 (2018). https://doi.org/10.1051/0004-6361/201833060
65. H.R. Neilson, J.B. Lester, Astron. Astrophys. **556**, A86 (2013). https://doi.org/10.1051/0004-6361/201321888
66. K.G. Stassun, R.D. Mathieu, J.A. Valenti, Nature **440**, 311 (2006). https://doi.org/10.1038/nature04570
67. K.G. Stassun, M. van den Berg, E. Feigelson, Astrophys. J. **660**, 704 (2007). https://doi.org/10.1086/513138
68. J. Irwin, S. Aigrain, S. Hodgkin, K.G. Stassun, L. Hebb, M. Irwin, E. Moraux, J. Bouvier, A. Alapini, R. Alexander, D.M. Bramich, J. Holtzman, E.L. Martín, M.J. McCaughrean, F. Pont, P.E. Verrier, M.R. Zapatero Osorio, Mon. Not. R. Astron. Soc. **380**, 541 (2007). https://doi.org/10.1111/j.1365-2966.2007.12117.x
69. M.J. McCaughrean, C.R. O'Dell, Astron. J. **111**, 1977 (1996)
70. L.A. Hillenbrand, Astron. J. **113**, 1733 (1997)
71. L.A. Hillenbrand, J.M. Carpenter, Astrophys. J. **540**, 236 (2000)
72. E.D. Feigelson, J.A. Gaffney, G. Garmire, L.A. Hillenbrand, L. Townsley, Astrophys. J. **584**, 911 (2003)
73. L.A. Hillenbrand, A.S. Hoffer, G.J. Herczeg, Astron. J. **146**, 85 (2013). https://doi.org/10.1088/0004-6256/146/4/85
74. P. Ingraham, L. Albert, R. Doyon, E. Artigau, Astrophys. J. **782**, 8 (2014). https://doi.org/10.1088/0004-637X/782/1/8

75. K.G. Stassun, R.D. Mathieu, P.A. Cargile, A.N. Aarnio, E. Stempels, A. Geller, Nature **453**, 1079 (2008). https://doi.org/10.1038/nature07069
76. P.A. Cargile, K.G. Stassun, R.D. Mathieu, Astrophys. J. **674**, 329 (2008). https://doi.org/10.1086/524346
77. Y. Gómez Maqueo Chew, K.G. Stassun, A. Prša, E. Stempels, L. Hebb, R. Barnes, R. Heller, R.D. Mathieu, Astrophys. J. **745**, 58 (2012). https://doi.org/10.1088/0004-637X/745/1/58
78. M. Morales-Calderón, J.R. Stauffer, K.G. Stassun, F.J. Vrba, L. Prato, L.A. Hillenbrand, S. Terebey, K.R. Covey, L.M. Rebull, D.M. Terndrup, R. Gutermuth, I. Song, P. Plavchan, J.M. Carpenter, F. Marchis, E.V. García, S. Margheim, K.L. Luhman, J. Angione, J.M. Irwin, Astrophys. J. **753**, 149 (2012). https://doi.org/10.1088/0004-637X/753/2/149
79. T. Preibisch, H. Zinnecker, Astron. J. **117**, 2381 (1999). https://doi.org/10.1086/300842
80. T. Preibisch, E. Guenther, H. Zinnecker, Astron. J. **121**, 1040 (2001). https://doi.org/10.1086/318774
81. C.L. Slesnick, L.A. Hillenbrand, J.M. Carpenter, Astrophys. J. **688**, 377 (2008). https://doi.org/10.1086/592265
82. M.J. Pecaut, E.E. Mamajek, E.J. Bubar, Astrophys. J. **746**, 154 (2012). https://doi.org/10.1088/0004-637X/746/2/154
83. I. Song, B. Zuckerman, M.S. Bessell, Astron. J. **144**, 8 (2012). https://doi.org/10.1088/0004-6256/144/1/8
84. M.J. Pecaut, in *IAU Symposium*, vol. 314, ed. by J.H. Kastner, B. Stelzer, S.A. Metchev (2016), pp. 85–90. https://doi.org/10.1017/S1743921315006079
85. A.C. Rizzuto, M.J. Ireland, T.J. Dupuy, A.L. Kraus, Astrophys. J. **817**, 164 (2016). https://doi.org/10.3847/0004-637X/817/2/164
86. T.J. David, L.A. Hillenbrand, E. Gillen, A.M. Cody, S.B. Howell, H.T. Isaacson, J.H. Livingston, Astrophys. J. **872**, 161 (2019). https://doi.org/10.3847/1538-4357/aafe09
87. C.L. Slesnick, J.M. Carpenter, L.A. Hillenbrand, Astron. J. **131**, 3016 (2006). https://doi.org/10.1086/503560
88. N. Lodieu, Mon. Not. R. Astron. Soc. **431**, 3222 (2013). https://doi.org/10.1093/MonthlyNoticesoftheRoyalAstronomicalSociety/stt402
89. P. Dawson, A. Scholz, T.P. Ray, K.A. Marsh, K. Wood, A. Natta, D. Padgett, M.E. Ressler, Mon. Not. R. Astron. Soc. **429**, 903 (2013). https://doi.org/10.1093/MonthlyNoticesoftheRoyalAstronomicalSociety/sts386
90. D. Ardila, E. Martín, G. Basri, Astron. J. **120**, 479 (2000)
91. A. Reiners, G. Basri, S. Mohanty, Astrophys. J. **634**, 1346 (2005). https://doi.org/10.1086/432878
92. A.L. Kraus, A.M. Cody, K.R. Covey, A.C. Rizzuto, A.W. Mann, M.J. Ireland, Astrophys. J. **807**, 3 (2015). https://doi.org/10.1088/0004-637X/807/1/3
93. T.J. David, L.A. Hillenbrand, A.M. Cody, J.M. Carpenter, A.W. Howard, Astrophys. J. **816**, 21 (2016). https://doi.org/10.3847/0004-637X/816/1/21
94. R. Alonso, H.J. Deeg, S. Hoyer, N. Lodieu, E. Palle, R. Sanchis-Ojeda, Astron. Astrophys. **584**, L8 (2015). https://doi.org/10.1051/0004-6361/201527109
95. J.R. Stauffer, G. Schultz, J.D. Kirkpatrick, Astrophys. J. Lett. **499**, 199 (1998)
96. D. Barrado y Navascués, J.R. Stauffer, R. Jayawardhana, Astrophys. J. **614**, 386 (2004)
97. P. Mazzei, L. Pigatto, Astron. Astrophys. **213**, L1 (1989)
98. S.E. Dahm, Astrophys. J. **813**, 108 (2015). https://doi.org/10.1088/0004-637X/813/2/108
99. S. Gossage, C. Conroy, A. Dotter, J. Choi, P. Rosenfield, P. Cargile, A. Dolphin, Astrophys. J. **863**, 67 (2018). https://doi.org/10.3847/1538-4357/aad0a0
100. N. Lodieu, A. Pérez-Garrido, R.L. Smart, R. Silvotti, A 5D view of the α Per, Pleiades, and Praesepe clusters. Astron. Astrophys. **628**, A66 (2019). https://doi.org/10.1051/0004-6361/201935533
101. A. Maeder, J.C. Mermilliod, Astron. Astrophys. **93**, 136 (1981)
102. J.C. Mermilliod, Astron. Astrophys. **97**, 235 (1981)
103. P. Mazzei, L. Pigatto, Astron. Astrophys. **193**, 148 (1988)

104. Y. Lebreton, J. Fernandes, T. Lejeune, Astron. Astrophys. **374**, 540 (2001). https://doi.org/10.1051/0004-6361:20010757
105. S. De Gennaro, T. von Hippel, W.H. Jefferys, N. Stein, D. van Dyk, E. Jeffery, Astrophys. J. **696**, 12 (2009). https://doi.org/10.1088/0004-637X/696/1/12
106. T.D. Brandt, C.X. Huang, Astrophys. J. **807**, 58 (2015). https://doi.org/10.1088/0004-637X/807/1/58
107. E.L. Martín, N. Lodieu, Y. Pavlenko, V.J.S. Béjar, Astrophys. J. **856**, 40 (2018). https://doi.org/10.3847/1538-4357/aaaeb8
108. N. Lodieu, R. Rebolo, A. Pérez-Garrido, Astron. Astrophys. **615**, L12 (2018). https://doi.org/10.1051/0004-6361/201832748
109. D.A. Vandenberg, T.J. Bridges, Astrophys. J. **278**, 679 (1984). https://doi.org/10.1086/161836
110. P. Delorme, A. Collier Cameron, L. Hebb, J. Rostron, T.A. Lister, A.J. Norton, D. Pollacco, R.G. West, Mon. Not. R. Astron. Soc. **413**, 2218 (2011). https://doi.org/10.1111/j.1365-2966.2011.18299.x
111. M. Salaris, A. Weiss, S.M. Percival, Astron. Astrophys. **414**, 163 (2004). https://doi.org/10.1051/0004-6361:20031578
112. C. Bonatto, E. Bica, L. Girardi, Astron. Astrophys. **415**, 571 (2004). https://doi.org/10.1051/0004-6361:20034638
113. Gaia Collaboration, C. Babusiaux, F. van Leeuwen, M.A. Barstow, C. Jordi, A. Vallenari, D. Bossini, A. Bressan, T. Cantat-Gaudin, M. van Leeuwen, et al., Astron. Astrophys. **616**, A10 (2018). https://doi.org/10.1051/0004-6361/201832843
114. A.M. Boesgaard, E.D. Friel, Astrophys. J. **351**, 467 (1990)
115. G. Cayrel de Strobel, F. Crifo, Y. Lebreton, in *Hipparcos - Venice '97*, *ESA Special Publication*, vol. 402, ed. by R.M. Bonnet, E. Høg, P.L. Bernacca, L. Emiliani, A. Blaauw, C. Turon, J. Kovalevsky, L. Lindegren, H. Hassan, M. Bouffard, B. Strim, D. Heger, M.A.C. Perryman, L. Woltjer (1997), pp. 687–688
116. M. Grenon, *IAU Joint Discussion*, vol. 13 (2000)
117. T.J. David, J. Stauffer, L.A. Hillenbrand, A.M. Cody, K. Conroy, K.G. Stassun, B. Pope, S. Aigrain, E. Gillen, A. Collier Cameron, D. Barrado, L.M. Rebull, H. Isaacson, G.W. Marcy, C. Zhang, R.L. Riddle, C. Ziegler, N.M. Law, C. Baranec, Astrophys. J. **814**, 62 (2015). https://doi.org/10.1088/0004-637X/814/1/62
118. T.J. David, K.E. Conroy, L.A. Hillenbrand, K.G. Stassun, J. Stauffer, L.M. Rebull, A.M. Cody, H. Isaacson, A.W. Howard, S. Aigrain, Astron. J. **151**, 112 (2016). https://doi.org/10.3847/0004-6256/151/5/112
119. L. Hebb, R.F.G. Wyse, G. Gilmore, J. Holtzman, Astron. J. **131**, 555 (2006). https://doi.org/10.1086/497971
120. W.S. Dias, B.S. Alessi, A. Moitinho, J.R.D. Lépine, Astron. Astrophys. **389**, 871 (2002). https://doi.org/10.1051/0004-6361:20020668
121. D.G. Turner, Astron. J. **104**, 1865 (1992). https://doi.org/10.1086/116363
122. A.L. Kraus, G.J. Herczeg, A.C. Rizzuto, A.W. Mann, C.L. Slesnick, J.M. Carpenter, L.A. Hillenbrand, E.E. Mamajek, Astrophys. J. **838**, 150 (2017). https://doi.org/10.3847/1538-4357/aa62a0
123. E. Gillen, L.A. Hillenbrand, T.J. David, S. Aigrain, L. Rebull, J. Stauffer, A.M. Cody, D. Queloz, Astrophys. J. **849**, 11 (2017). https://doi.org/10.3847/1538-4357/aa84b3
124. J.D. Adams, J.R. Stauffer, M.F. Skrutskie, D.G. Monet, S.F. Portegies Zwart, K.A. Janes, C.A. Beichman, Astron. J. **124**, 1570 (2002). https://doi.org/10.1086/342016
125. A.L. Kraus, L.A. Hillenbrand, Astron. J. **134**, 2340 (2007). https://doi.org/10.1086/522831
126. D.E.A. Baker, R.F. Jameson, S.L. Casewell, N. Deacon, N. Lodieu, N. Hambly, Mon. Not. R. Astron. Soc. **408**, 2457 (2010). https://doi.org/10.1111/j.1365-2966.2010.17302.x
127. S. Boudreault, N. Lodieu, N.R. Deacon, N.C. Hambly, Mon. Not. R. Astron. Soc. **426**, 3419 (2012). https://doi.org/10.1111/j.1365-2966.2012.21854.x
128. P. Khalaj, H. Baumgardt, Mon. Not. R. Astron. Soc. **434**, 3236 (2013). https://doi.org/10.1093/MonthlyNoticesoftheRoyalAstronomicalSociety/stt1239

129. P.F. Wang, W.P. Chen, C.C. Lin, A.K. Pandey, C.K. Huang, N. Panwar, C.H. Lee, M.F. Tsai, C.H. Tang, B. Goldman, W.S. Burgett, K.C. Chambers, P.W. Draper, H. Flewelling, T. Grav, J.N. Heasley, K.W. Hodapp, M.E. Huber, R. Jedicke, N. Kaiser, R.P. Kudritzki, G.A. Luppino, R.H. Lupton, E.A. Magnier, N. Metcalfe, D.G. Monet, J.S. Morgan, P.M. Onaka, P.A. Price, C.W. Stubbs, W. Sweeney, J.L. Tonry, R.J. Wainscoat, C. Waters, Astrophys. J. **784**, 57 (2014). https://doi.org/10.1088/0004-637X/784/1/57
130. A.W. Mann, E. Gaidos, A. Vanderburg, A.C. Rizzuto, M. Ansdell, J.V. Medina, G.N. Mace, A.L. Kraus, K.R. Sokal, Astron. J. **153**, 64 (2017). https://doi.org/10.1088/1361-6528/aa5276
131. W.F. van Altena, Astron. J. **71**, 482 (1966). https://doi.org/10.1086/109952
132. R.B. Hanson, Astron. J. **80**, 379 (1975). https://doi.org/10.1086/111753
133. A.W. Mann, E. Gaidos, G.N. Mace, M.C. Johnson, B.P. Bowler, D. LaCourse, T.L. Jacobs, A. Vanderburg, A.L. Kraus, K.F. Kaplan, D.T. Jaffe, Astrophys. J. **818**, 46 (2016). https://doi.org/10.3847/0004-637X/818/1/46
134. N. Lodieu, R.L. Smart, A. Pérez-Garrido, R. Silvotti, A 3D view of the Hyades stellar and sub-stellar population. Astron. Astrophys. **623**, A35 (2019). https://doi.org/10.1051/0004-6361/201834045
135. H. Baumgardt, M. Hilker, Mon. Not. R. Astron. Soc. **478**, 1520 (2018). https://doi.org/10.1093/mnras/sty1057
136. L.J. Rossi, S. Ortolani, B. Barbuy, E. Bica, A. Bonfanti, Mon. Not. R. Astron. Soc. **450**, 3270 (2015). https://doi.org/10.1093/mnras/stv748
137. E. Bica, C. Bonatto, B. Barbuy, S. Ortolani, Astron. Astrophys. **450**, 105 (2006). https://doi.org/10.1051/0004-6361:20054351
138. G. Piotto, L.R. Bedin, J. Anderson, I.R. King, S. Cassisi, A.P. Milone, S. Villanova, A. Pietrinferni, A. Renzini, Astrophys. J. Lett. **661**, L53 (2007). https://doi.org/10.1086/518503
139. S. Cassisi, M. Salaris, A. Pietrinferni, D. Hyder, Mon. Not. R. Astron. Soc. **464**, 2341 (2017). https://doi.org/10.1093/mnras/stw2579
140. J. Kaluzny, S.M. Rucinski, I.B. Thompson, W. Pych, W. Krzeminski, Astron. J. **133**, 2457 (2007). https://doi.org/10.1086/516637
141. J. Kaluzny, I.B. Thompson, A. Dotter, M. Rozyczka, A. Schwarzenberg-Czerny, G.S. Burley, B. Mazur, S.M. Rucinski, Astron. J. **150**, 155 (2015). https://doi.org/10.1088/0004-6256/150/5/155
142. A.R. Sandage, Astron. J. **58**, 61 (1953). https://doi.org/10.1086/106822
143. A. Sollima, G. Beccari, F.R. Ferraro, F. Fusi Pecci, A. Sarajedini, Mon. Not. R. Astron. Soc. **380**, 781 (2007). https://doi.org/10.1111/j.1365-2966.2007.12116.x
144. J. Ji, J.N. Bregman, Astrophys. J. **768**, 158 (2013). https://doi.org/10.1088/0004-637X/768/2/158
145. S. Lucatello, A. Sollima, R. Gratton, E. Vesperini, V. D'Orazi, E. Carretta, A. Bragaglia, Astron. Astrophys. **584**, A52 (2015). https://doi.org/10.1051/0004-6361/201526957
146. A.P. Milone, A.F. Marino, L.R. Bedin, A. Dotter, H. Jerjen, D. Kim, D. Nardiello, G. Piotto, J. Cong, Mon. Not. R. Astron. Soc. **455**, 3009 (2016). https://doi.org/10.1093/mnras/stv2415
147. C.M. Clement, A. Muzzin, Q. Dufton, T. Ponnampalam, J. Wang, J. Burford, A. Richardson, T. Rosebery, J. Rowe, H.S. Hogg, Astron. J. **122**, 2587 (2001). https://doi.org/10.1086/323719
148. J.R. Percy, *Understanding Variable Stars* (Cambridge University Press, Cambridge, 2011)
149. D. Deras, A. Arellano Ferro, C. Lázaro, I.H. Bustos Fierro, J.H. Calderón, S. Muneer, S. Giridhar, Mon. Not. R. Astron. Soc. **486**, 2791 (2019). https://doi.org/10.1093/mnras/stz642
150. M.A. Yepez, A. Arellano Ferro, S. Muneer, S. Giridhar, Rev. Mex. Astron. Astrofis. **54**, 15 (2018)
151. M. Rozyczka, I.B. Thompson, W. Pych, W. Narloch, R. Poleski, A. Schwarzenberg-Czerny, Acta Astronom. **67**, 203 (2017). https://doi.org/10.32023/0001-5237/67.3.1
152. Y. Tsapras, A. Arellano Ferro, D.M. Bramich, R.F. Jaimes, N. Kains, R. Street, M. Hundertmark, K. Horne, M. Dominik, C. Snodgrass, Mon. Not. R. Astron. Soc. **465**, 2489 (2017). https://doi.org/10.1093/mnras/stw2773

153. D.J. Lee, J.R. Koo, K. Hong, S.L. Kim, J.W. Lee, C.U. Lee, Y.B. Jeon, Y.H. Kim, B. Lim, Y.H. Ryu, S.M. Cha, Y. Lee, D.J. Kim, B.G. Park, C.H. Kim, J. Korean Astron. Soc. **49**, 295 (2016). https://doi.org/10.5303/JKAS.2016.49.6.295
154. D.A. Fischer, G.W. Marcy, Astrophys. J. **396**, 178 (1992)
155. D. Baroch, J.C. Morales, I. Ribas, L. Tal-Or, M. Zechmeister, A. Reiners, J.A. Caballero, A. Quirrenbach, P.J. Amado, S. Dreizler, S. Lalitha, S.V. Jeffers, M. Lafarga, V.J.S. Béjar, J. Colomé, M. Cortés-Contreras, E. Díez-Alonso, D. Galadí-Enríquez, E.W. Guenther, H.J. Hagen, T. Henning, E. Herrero, M. Kürster, D. Montes, E. Nagel, V.M. Passegger, M. Perger, A. Rosich, A. Schweitzer, W. Seifert, Astron. Astrophys. **619**, A32 (2018). https://doi.org/10.1051/0004-6361/201833440
156. B.M. Clark, C.H. Blake, G.R. Knapp, Astrophys. J. **744**, 119 (2012). https://doi.org/10.1088/0004-637X/744/2/119
157. G. Basri, A. Reiners, Astron. J. **132**, 663 (2006). https://doi.org/10.1086/505198
158. C.H. Blake, D. Charbonneau, R.J. White, Astrophys. J. **723**(1), 684 (2010). https://doi.org/10.1088/0004-637X/723/1/684
159. Y. Shan, J.A. Johnson, T.D. Morton, Astrophys. J. **813**, 75 (2015). https://doi.org/10.1088/0004-637X/813/1/75
160. L.M. Rebull, J.R. Stauffer, J. Bouvier, A.M. Cody, L.A. Hillenbrand, D.R. Soderblom, J. Valenti, D. Barrado, H. Bouy, D. Ciardi, M. Pinsonneault, K. Stassun, G. Micela, S. Aigrain, F. Vrba, G. Somers, E. Gillen, A. Collier Cameron, Astron. J. **152**, 114 (2016). https://doi.org/10.3847/0004-6256/152/5/114
161. J. Stauffer, L. Rebull, J. Bouvier, L.A. Hillenbrand, A. Collier-Cameron, M. Pinsonneault, S. Aigrain, D. Barrado, H. Bouy, D. Ciardi, A.M. Cody, T. David, G. Micela, D. Soderblom, G. Somers, K.G. Stassun, J. Valenti, F.J. Vrba, Astron. J. **152**, 115 (2016). https://doi.org/10.3847/0004-6256/152/5/115
162. L.M. Rebull, J.R. Stauffer, L.A. Hillenbrand, A.M. Cody, J. Bouvier, D.R. Soderblom, M. Pinsonneault, L. Hebb, Astrophys. J. (2017)
163. L.M. Rebull, J.R. Stauffer, A.M. Cody, L.A. Hillenbrand, T.J. David, M. Pinsonneault, Astron. J. **155**, 196 (2018). https://doi.org/10.3847/1538-3881/aab605
164. K.G. Stassun, R.D. Mathieu, J.A. Valenti, Astrophys. J. **664**, 1154 (2007). https://doi.org/10.1086/519231
165. A. Burrows, J. Liebert, Rev. Mod. Phys. **65**, 301 (1993)
166. I. Baraffe, G. Chabrier, F. Allard, P.H. Hauschildt, Astron. Astrophys. **337**, 403 (1998)
167. I. Baraffe, D. Homeier, F. Allard, G. Chabrier, Astron. Astrophys. **577**, A42 (2015). https://doi.org/10.1051/0004-6361/201425481
168. E. Gillen, S. Aigrain, A. McQuillan, J. Bouvier, S. Hodgkin, S.H.P. Alencar, C. Terquem, J. Southworth, N.P. Gibson, A. Cody, M. Lendl, M. Morales-Calderón, F. Favata, J. Stauffer, G. Micela, Astron. Astrophys. **562**, A50 (2014). https://doi.org/10.1051/0004-6361/201322493
169. D.R. Anderson, A. Collier Cameron, C. Hellier, M. Lendl, P.F.L. Maxted, D. Pollacco, D. Queloz, B. Smalley, A.M.S. Smith, I. Todd, A.H.M.J. Triaud, R.G. West, S.C.C. Barros, B. Enoch, M. Gillon, T.A. Lister, F. Pepe, D. Ségransan, R.A. Street, S. Udry, Astrophys. J. Lett. **726**, L19 (2011). https://doi.org/10.1088/2041-8205/726/2/L19
170. R.F. Díaz, G. Montagnier, J. Leconte, A.S. Bonomo, M. Deleuil, J.M. Almenara, S.C.C. Barros, F. Bouchy, G. Bruno, C. Damiani, G. Hébrard, C. Moutou, A. Santerne, Astron. Astrophys. **572**, A109 (2014). https://doi.org/10.1051/0004-6361/201424406
171. A.S. Bonomo, A. Sozzetti, A. Santerne, M. Deleuil, J.M. Almenara, G. Bruno, R.F. Díaz, G. Hébrard, C. Moutou, Astron. Astrophys. **575**, A85 (2015). https://doi.org/10.1051/0004-6361/201323042
172. F. Bouchy, M. Deleuil, T. Guillot, S. Aigrain, L. Carone, W.D. Cochran, J.M. Almenara, R. Alonso, M. Auvergne, A. Baglin, P. Barge, A.S. Bonomo, P. Bordé, S. Csizmadia, K. de Bondt, H.J. Deeg, R.F. Díaz, R. Dvorak, M. Endl, A. Erikson, S. Ferraz-Mello, M. Fridlund, D. Gandolfi, J.C. Gazzano, N. Gibson, M. Gillon, E. Guenther, A. Hatzes, M. Havel, G. Hébrard, L. Jorda, A. Léger, C. Lovis, A. Llebaria, H. Lammer, P.J. MacQueen, T. Mazeh,

C. Moutou, A. Ofir, M. Ollivier, H. Parviainen, M. Pätzold, D. Queloz, H. Rauer, D. Rouan, A. Santerne, J. Schneider, B. Tingley, G. Wuchterl, Astron. Astrophys. **525**, A68 (2011). https://doi.org/10.1051/0004-6361/201015276
173. S. Csizmadia, A. Hatzes, D. Gandolfi, M. Deleuil, F. Bouchy, M. Fridlund, L. Szabados, H. Parviainen, J. Cabrera, S. Aigrain, R. Alonso, J.M. Almenara, A. Baglin, P. Bordé, A.S. Bonomo, H.J. Deeg, R.F. Díaz, A. Erikson, S. Ferraz-Mello, M. Tadeu dos Santos, E.W. Guenther, T. Guillot, S. Grziwa, G. Hébrard, P. Klagyivik, M. Ollivier, M. Pätzold, H. Rauer, D. Rouan, A. Santerne, J. Schneider, T. Mazeh, G. Wuchterl, S. Carpano, A. Ofir, Astron. Astrophys. **584**, A13 (2015). https://doi.org/10.1051/0004-6361/201526763
174. R.J. Siverd, T.G. Beatty, J. Pepper, J.D. Eastman, K. Collins, A. Bieryla, D.W. Latham, L.A. Buchhave, E.L.N. Jensen, J.R. Crepp, R. Street, K.G. Stassun, B.S. Gaudi, P. Berlind, M.L. Calkins, D.L. DePoy, G.A. Esquerdo, B.J. Fulton, G. Fűrész, J.C. Geary, A. Gould, L. Hebb, J.F. Kielkopf, J.L. Marshall, R. Pogge, K.Z. Stanek, R.P. Stefanik, A.H. Szentgyorgyi, M. Trueblood, P. Trueblood, A.M. Stutz, J.L. van Saders, Astrophys. J. **761**, 123 (2012). https://doi.org/10.1088/0004-637X/761/2/123
175. E.E. Mamajek, L.A. Hillenbrand, Astrophys. J. **687**, 1264 (2008). https://doi.org/10.1086/591785
176. J. Irwin, L. Buchhave, Z.K. Berta, D. Charbonneau, D.W. Latham, C.J. Burke, G.A. Esquerdo, M.E. Everett, M.J. Holman, P. Nutzman, P. Berlind, M.L. Calkins, E.E. Falco, J.N. Winn, J.A. Johnson, J.Z. Gazak, Astrophys. J. **718**, 1353 (2010). https://doi.org/10.1088/0004-637X/718/2/1353
177. M. Deleuil, H.J. Deeg, R. Alonso, F. Bouchy, D. Rouan, M. Auvergne, A. Baglin, S. Aigrain, J.M. Almenara, M. Barbieri, P. Barge, H. Bruntt, P. Bordé, A. Collier Cameron, S. Csizmadia, R. de La Reza, R. Dvorak, A. Erikson, M. Fridlund, D. Gandolfi, M. Gillon, E. Guenther, T. Guillot, A. Hatzes, G. Hébrard, L. Jorda, H. Lammer, A. Léger, A. Llebaria, B. Loeillet, M. Mayor, T. Mazeh, C. Moutou, M. Ollivier, M. Pätzold, F. Pont, D. Queloz, H. Rauer, J. Schneider, A. Shporer, G. Wuchterl, S. Zucker, Astron. Astrophys. **491**, 889 (2008). https://doi.org/10.1051/0004-6361:200810625
178. N.I. Gorlova, M.R. Meyer, G.H. Rieke, J. Liebert, Astrophys. J. **593**, 1074 (2003)
179. J. Gagné, D. Lafrenière, R. Doyon, L. Malo, É. Artigau, Astrophys. J. **783**, 121 (2014). https://doi.org/10.1088/0004-637X/783/2/121
180. J.C. Filippazzo, E.L. Rice, J. Faherty, K.L. Cruz, M.M. Van Gordon, D.L. Looper, Astrophys. J. **810**, 158 (2015). https://doi.org/10.1088/0004-637X/810/2/158
181. E.C. Martin, G.N. Mace, I.S. McLean, S.E. Logsdon, E.L. Rice, J.D. Kirkpatrick, A.J. Burgasser, M.R. McGovern, L. Prato, Surface Gravities for 228 M, L, and T Dwarfs in the NIRSPEC Brown Dwarf Spectroscopic Survey. Astrophys. J. **838**(1), 73 (2017). https://doi.org/10.3847/1538-4357/aa6338
182. N. Lodieu, M.R. Zapatero Osorio, V.J.S. Béjar, K. Peña Ramírez, Mon. Not. R. Astron. Soc. **473**, 2020 (2018). https://doi.org/10.1093/MonthlyNoticesoftheRoyalAstronomicalSociety/stx2279
183. N.C. Santos, G. Israelian, M. Mayor, J.P. Bento, P.C. Almeida, S.G. Sousa, A. Ecuvillon, Astron. Astrophys. **437**, 1127 (2005). https://doi.org/10.1051/0004-6361:20052895
184. J.C. Bond, C.G. Tinney, R.P. Butler, H.R.A. Jones, G.W. Marcy, A.J. Penny, B.D. Carter, Mon. Not. R. Astron. Soc. **370**, 163 (2006). https://doi.org/10.1111/j.1365-2966.2006.10459.x
185. N.C. Santos, G. Israelian, M. Mayor, R. Rebolo, S. Udry, Astron. Astrophys. **398**, 363 (2003). https://doi.org/10.1051/0004-6361:20021637
186. R. Pinotti, L. Arany-Prado, W. Lyra, G.F. Porto de Mello, Mon. Not. R. Astron. Soc. **364**, 29 (2005). https://doi.org/10.1111/j.1365-2966.2005.09491.x
187. K. El-Badry, H.W. Rix, Mon. Not. R. Astron. Soc. **482**, L139 (2019). https://doi.org/10.1093/MonthlyNoticesoftheRoyalAstronomicalSocietyl/sly206
188. J.E. Gizis, I.N. Reid, Astron. J. **117**, 508 (1999)
189. S. Lépine, R.M. Rich, M.M. Shara, Astrophys. J. **669**, 1235 (2007). https://doi.org/10.1086/521614

190. A.J. Burgasser, K.L. Cruz, J.D. Kirkpatrick, Astrophys. J. **657**, 494 (2007). https://doi.org/10.1086/510148
191. W.C. Jao, T.J. Henry, T.D. Beaulieu, J.P. Subasavage, Astron. J. **136**, 840 (2008). https://doi.org/10.1088/0004-6256/136/2/840
192. J.D. Kirkpatrick, K. Kellogg, A.C. Schneider, S. Fajardo-Acosta, M.C. Cushing, J. Greco, G.N. Mace, C.R. Gelino, E.L. Wright, P.R.M. Eisenhardt, D. Stern, J.K. Faherty, S.S. Sheppard, G.B. Lansbury, S.E. Logsdon, E.C. Martin, I.S. McLean, S.D. Schurr, R.M. Cutri, T. Conrow, Astrophys. J. Suppl. Ser. **224**, 36 (2016). https://doi.org/10.3847/0067-0049/224/2/36
193. Z.H. Zhang, D.J. Pinfield, M.C. Gálvez-Ortiz, B. Burningham, N. Lodieu, F. Marocco, A.J. Burgasser, A.C. Day-Jones, F. Allard, H.R.A. Jones, D. Homeier, J. Gomes, R.L. Smart, Mon. Not. R. Astron. Soc. **464**, 3040 (2017). https://doi.org/10.1093/MonthlyNoticesoftheRoyalAstronomicalSociety/stw2438
194. C. Moutou, A.S. Bonomo, G. Bruno, G. Montagnier, F. Bouchy, J.M. Almenara, S.C.C. Barros, M. Deleuil, R.F. Díaz, G. Hébrard, A. Santerne, Astron. Astrophys. **558**, L6 (2013). https://doi.org/10.1051/0004-6361/201322201
195. M.J. Phillips, L. Hartmann, Astrophys. J. **224**, 182 (1978). https://doi.org/10.1086/156363
196. O.C. Wilson, Astrophys. J. **226**, 379 (1978). https://doi.org/10.1086/156618
197. S.L. Baliunas, E. Nesme-Ribes, D. Sokoloff, W.H. Soon, Astrophys. J. **460**, 848 (1996). https://doi.org/10.1086/177014
198. G.W. Lockwood, B.A. Skiff, G.W. Henry, S. Henry, R.R. Radick, S.L. Baliunas, R.A. Donahue, W. Soon, Astrophys. J. Suppl. Ser. **171**, 260 (2007). https://doi.org/10.1086/516752
199. S. Messina, E.F. Guinan, Astron. Astrophys. **393**, 225 (2002). https://doi.org/10.1051/0004-6361:20021000
200. K. Oláh, Z. Kolláth, T. Granzer, K.G. Strassmeier, A.F. Lanza, S. Järvinen, H. Korhonen, S.L. Baliunas, W. Soon, S. Messina, G. Cutispoto, Astron. Astrophys. **501**, 703 (2009). https://doi.org/10.1051/0004-6361/200811304
201. L. Jetsu, J. Pelt, I. Tuominen, Astron. Astrophys. **278**, 449 (1993)
202. P. Parihar, S. Messina, P. Bama, B.J. Medhi, S. Muneer, C. Velu, A. Ahmad, Mon. Not. R. Astron. Soc. **395**, 593 (2009). https://doi.org/10.1111/j.1365-2966.2009.14422.x
203. Z. Eker, N.F. Ak, S. Bilir, D. Doğru, M. Tüysüz, E. Soydugan, H. Bakış, B. Uğraş, F. Soydugan, A. Erdem, O. Demircan, Mon. Not. R. Astron. Soc. **389**, 1722 (2008). https://doi.org/10.1111/j.1365-2966.2008.13670.x
204. C.A. Watson, V.S. Dhillon, Mon. Not. R. Astron. Soc. **351**, 110 (2004). https://doi.org/10.1111/j.1365-2966.2004.07763.x
205. S. Czesla, S. Terzenbach, R. Wichmann, J.H.M.M. Schmitt, Astron. Astrophys. **623**, A107 (2019). https://doi.org/10.1051/0004-6361/201834516
206. R.A. Osten, A. Kowalski, S.A. Drake, H. Krimm, K. Page, K. Gazeas, J. Kennea, S. Oates, M. Page, E. de Miguel, R. Novák, T. Apeltauer, N. Gehrels, Astrophys. J. **832**, 174 (2016). https://doi.org/10.3847/0004-637X/832/2/174
207. J.R.A. Davenport, Astrophys. J. **829**(1), 23 (2016). https://doi.org/10.3847/0004-637X/829/1/23
208. E. Ilin, S.J. Schmidt, J.R.A. Davenport, K.G. Strassmeier, Astron. Astrophys. **622**, A133 (2019). https://doi.org/10.1051/0004-6361/201834400
209. T. Van Doorsselaere, H. Shariati, J. Debosscher, Astrophys. J. Suppl. Ser. **232**(2), 26 (2017). https://doi.org/10.3847/1538-4365/aa8f9a
210. S.L. Hawley, J.R.A. Davenport, A.F. Kowalski, J.P. Wisniewski, L. Hebb, R. Deitrick, E.J. Hilton, Astrophys. J. **797**(2), 121 (2014). https://doi.org/10.1088/0004-637X/797/2/121
211. M.N. Günther, Z. Zhan, S. Seager, P.B. Rimmer, S. Ranjan, K.G. Stassun, R.J. Oelkers, T. Daylan, E. Newton, E. Gillen (2019). e-prints arXiv:1901.00443
212. J.A.G. Jackman, P.J. Wheatley, C.E. Pugh, D.Y. Kolotkov, A.M. Broomhall, G.M. Kennedy, S.J. Murphy, R. Raddi, M.R. Burleigh, S.L. Casewell, Mon. Not. R. Astron. Soc. **482**(4), 5553 (2019). https://doi.org/10.1093/mnras/sty3036

213. S.J. Schmidt, B.J. Shappee, J.L. van Saders, K.Z. Stanek, J.S. Brown, C.S. Kochanek, S. Dong, M.R. Drout, S. Frank, T.W.S. Holoien, Astrophys. J. **876**(2), 115 (2019). https://doi.org/10.3847/1538-4357/ab148d
214. H.Y. Chang, Y.H. Song, A.L. Luo, L.C. Huang, W.H. Ip, J.N. Fu, Y. Zhang, Y.H. Hou, Z.H. Cao, Y.F. Wang, Astrophys. J. **834**(1), 92 (2017). https://doi.org/10.3847/1538-4357/834/1/92
215. J.C. Morales, I. Ribas, C. Jordi, G. Torres, J. Gallardo, E.F. Guinan, D. Charbonneau, M. Wolf, D.W. Latham, G. Anglada-Escudé, Astrophys. J. **691**(2), 1400 (2009). https://doi.org/10.1088/0004-637X/691/2/1400
216. G. Torres, I. Ribas, Astrophys. J. **567**(2), 1140 (2002). https://doi.org/10.1086/338587
217. I. Ribas, Astron. Astrophys. **398**, 239 (2003). https://doi.org/10.1051/0004-6361:20021609
218. M. López-Morales, I. Ribas, Astrophys. J. **631**(2), 1120 (2005). https://doi.org/10.1086/432680
219. G. Torres, Astron. Nachr. **334**(1–2), 4 (2013). https://doi.org/10.1002/asna.201211743
220. G.A. Feiden, B. Chaboyer, Astron. Astrophys. **571**, A70 (2014). https://doi.org/10.1051/0004-6361/201424288
221. G.R. Ricker, J.N. Winn, R. Vanderspek, D.W. Latham, G.Á. Bakos, J.L. Bean, Z.K. Berta-Thompson, T.M. Brown, L. Buchhave, N.R. Butler, R.P. Butler, W.J. Chaplin, D. Charbonneau, J. Christensen-Dalsgaard, M. Clampin, D. Deming, J. Doty, N. De Lee, C. Dressing, E.W. Dunham, M. Endl, F. Fressin, J. Ge, T. Henning, M.J. Holman, A.W. Howard, S. Ida, J.M. Jenkins, G. Jernigan, J.A. Johnson, L. Kaltenegger, N. Kawai, H. Kjeldsen, G. Laughlin, A.M. Levine, D. Lin, J.J. Lissauer, P. MacQueen, G. Marcy, P.R. McCullough, T.D. Morton, N. Narita, M. Paegert, E. Palle, F. Pepe, J. Pepper, A. Quirrenbach, S.A. Rinehart, D. Sasselov, B. Sato, S. Seager, A. Sozzetti, K.G. Stassun, P. Sullivan, A. Szentgyorgyi, G. Torres, S. Udry, J. Villasenor, J. Astron. Telescopes Instrum. Syst. **1**(1), 014003 (2015). https://doi.org/10.1117/1.JATIS.1.1.014003
222. I. Roxburgh, C. Catala, PLATO Consortium, Commun. Asteroseismol. **150**, 357 (2007). https://doi.org/10.1553/cia150s357
223. S. Raetz, T.O.B. Schmidt, S. Czesla, T. Klocová, L. Holmes, R. Errmann, M. Kitze, M. Fernández, A. Sota, C. Briceño, J. Hernández, J.J. Downes, D.P. Dimitrov, D. Kjurkchieva, V. Radeva, Z.Y. Wu, X. Zhou, H. Takahashi, T. Henych, M. Seeliger, M. Mugrauer, C. Adam, C. Marka, J.G. Schmidt, M.M. Hohle, C. Ginski, T. Pribulla, L. Trepl, M. Moualla, N. Pawellek, J. Gelszinnis, S. Buder, S. Masda, G. Maciejewski, R. Neuhäuser, Mon. Not. R. Astron. Soc. **460**, 2834 (2016). https://doi.org/10.1093/MonthlyNoticesoftheRoyalAstronomicalSociety/stw1159
224. R. Errmann, R. Neuhäuser, L. Marschall, G. Torres, M. Mugrauer, W.P. Chen, S.C.L. Hu, C. Briceno, R. Chini, Ł. Bukowiecki, D.P. Dimitrov, D. Kjurkchieva, E.L.N. Jensen, D.H. Cohen, Z.Y. Wu, T. Pribulla, M. Vaňko, V. Krushevska, J. Budaj, Y. Oasa, A.K. Pandey, M. Fernandez, A. Kellerer, C. Marka, Astron. Nachr. **334**, 673 (2013). https://doi.org/10.1002/asna.201311890
225. Z. Garai, T. Pribulla, L'. Hambálek, R. Errmann, C. Adam, S. Buder, T. Butterley, V.S. Dhillon, B. Dincel, H. Gilbert, C. Ginski, L.K. Hardy, A. Kellerer, M. Kitze, E. Kundra, S.P. Littlefair, M. Mugrauer, J. Nedoroščík, R. Neuhäuser, A. Pannicke, S. Raetz, J.G. Schmidt, T.O.B. Schmidt, M. Seeliger, M. Vaňko, R.W. Wilson, Astron. Nachr. **337**, 261 (2016). https://doi.org/10.1002/asna.201512310
226. P.D. Dobbie, N. Lodieu, R.G. Sharp, Mon. Not. R. Astron. Soc. **409**, 1002 (2010). https://doi.org/10.1111/j.1365-2966.2010.17355.x
227. S. Manzi, S. Randich, W.J. de Wit, F. Palla, Astron. Astrophys. **479**, 141 (2008). https://doi.org/10.1051/0004-6361:20078226
228. D. Barrado y Navascués, J. Bouvier, J.R. Stauffer, N. Lodieu, M.J. McCaughrean, Astron. Astrophys. **395**, 813 (2002)
229. M. Hünsch, S. Randich, M. Hempel, C. Weidner, J.H.M.M. Schmitt, Astron. Astrophys. **418**, 539 (2004). https://doi.org/10.1051/0004-6361:20040043

230. J.P. Emerson, in *The New Era of Wide Field Astronomy, Astronomical Society of the Pacific Conference Series*, vol. 232, ed. by R. Clowes, A. Adamson, and G. Bromage (2001), p. 339
231. G.B. Dalton, M. Caldwell, A.K. Ward, M.S. Whalley, G. Woodhouse, R.L. Edeson, P. Clark, S.M. Beard, A.M. Gallie, S.P. Todd, J.M.D. Strachan, N.N. Bezawada, W.J. Sutherland, J.P. Emerson, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, vol. 6269 (2006). https://doi.org/10.1117/12.670018
232. P.J. Wheatley, D.L. Pollacco, D. Queloz, H. Rauer, C.A. Watson, R.G. West, B. Chazelas, T.M. Louden, S. Walker, N. Bannister, J. Bento, M. Burleigh, J. Cabrera, P. Eigmüller, A. Erikson, L. Genolet, M. Goad, A. Grange, A. Jordán, K. Lawrie, J. McCormac, M. Neveu, *European Physical Journal Web of Conferences, European Physical Journal Web of Conferences*, vol. 47 (2013), p. 13002. https://doi.org/10.1051/epjconf/20134713002
233. M. Gillon, E. Jehin, P. Magain, V. Chantry, D. Hutsemékers, J. Manfroid, D. Queloz, S. Udry, *European Physical Journal Web of Conferences, European Physical Journal Web of Conferences*, vol. 11 (2011), p. 06002. https://doi.org/10.1051/epjconf/20101106002
234. M. Gillon, E. Jehin, L. Delrez, P. Magain, C. Opitom, S. Sohy, *Protostars and Planets VI Posters* (2013)
235. R. Alonso, T.M. Brown, G. Torres, D.W. Latham, A. Sozzetti, G. Mandushev, J.A. Belmonte, D. Charbonneau, H.J. Deeg, E.W. Dunham, F.T. O'Donovan, R.P. Stefanik, Astrophys. J. Lett. **613**, L153 (2004). https://doi.org/10.1086/425256
236. G.Á. Bakos, J. Lázár, I. Papp, P. Sári, E.M. Green, Publ. Astron. Soc. Pac. **114**, 974 (2002). https://doi.org/10.1086/342382
237. D.L. Pollacco, I. Skillen, A. Collier Cameron, D.J. Christian, C. Hellier, J. Irwin, T.A. Lister, R.A. Street, R.G. West, D.R. Anderson, W.I. Clarkson, H. Deeg, B. Enoch, A. Evans, A. Fitzsimmons, C.A. Haswell, S. Hodgkin, K. Horne, S.R. Kane, F.P. Keenan, P.F.L. Maxted, A.J. Norton, J. Osborne, N.R. Parley, R.S.I. Ryans, B. Smalley, P.J. Wheatley, D.M. Wilson, Publ. Astron. Soc. Pac. **118**, 1407 (2006). https://doi.org/10.1086/508556
238. P.R. McCullough, J.E. Stys, J.A. Valenti, S.W. Fleming, K.A. Janes, J.N. Heasley, Publ. Astron. Soc. Pac. **117**, 783 (2005). https://doi.org/10.1086/432024
239. J. Pepper, R.W. Pogge, D.L. DePoy, J.L. Marshall, K.Z. Stanek, A.M. Stutz, S. Poindexter, R. Siverd, T.P. O'Brien, M. Trueblood, P. Trueblood, Publ. Astron. Soc. Pac. **119**, 923 (2007). https://doi.org/10.1086/521836
240. D. Montes, J. López-Santiago, M.J. Fernández-Figueroa, M.C. Gálvez, Astron. Astrophys. **379**, 976 (2001). https://doi.org/10.1051/0004-6361:20011385
241. B. Zuckerman, I. Song, Annu. Rev. Astron. Astrophys. **42**, 685 (2004)
242. T. Antoja, F. Figueras, D. Fernández, J. Torra, Astron. Astrophys. **490**, 135 (2008). https://doi.org/10.1051/0004-6361:200809519
243. S. Hubrig, O. Marco, B. Stelzer, M. Schöller, N. Huélamo, Mon. Not. R. Astron. Soc. **381**, 1569 (2007). https://doi.org/10.1111/j.1365-2966.2007.12325.x
244. I.N. Evans, F. Civano, Astron. Geophys. **59**(2), 2.17 (2018). https://doi.org/10.1093/astrogeo/aty079
245. T. Boller, M.J. Freyberg, J. Trümper, F. Haberl, W. Voges, K. Nandra, Astron. Astrophys. **588**, A103 (2016). https://doi.org/10.1051/0004-6361/201525648
246. I. Traulsen, A.D. Schwope, G. Lamer, J. Ballet, F. Carrera, M. Coriat, M.J. Freyberg, L. Michel, C. Motch, S.R. Rosen, N. Webb, M.T. Ceballos, F. Koliopanos, J. Kurpas, M.J. Page, M.G. Watson, Astron. Astrophys. **624**, A77 (2019). https://doi.org/10.1051/0004-6361/201833938
247. C. Schröder, J.H.M.M. Schmitt, Astron. Astrophys. **475**, 677 (2007). https://doi.org/10.1051/0004-6361:20077429
248. B. Stelzer, A. Marino, G. Micela, J. López-Santiago, C. Liefke, Mon. Not. R. Astron. Soc. **431**, 2063 (2013). https://doi.org/10.1093/mnras/stt225