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A Rare Pair of Eclipsing Brown Dwarfs Identified by the SPECULOOS Telescopes

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Brown dwarfs — stellar objects unable to sustain hydrogen fusion in their cores because of their low masses — continuously cool over their lifetimes. Evolution models have been created to reproduce this behaviour, and to allow mass and age determination using their luminosity, temperatures, spectral types and other parameters. However, these models have not yet been fully validated or calibrated with observations. During a commissioning run of the SPECULOOS telescopes, we serendipitously discovered a rare double-line eclipsing binary, a member of the 45 Myr-old moving group Argus. This discovery permitted us to determine the masses, radii and ages of the brown dwarfs, and with their luminosities make a comparison to evolution models. The models reproduce these measurements remarkably well, although a measured offset in luminosity could result in systematic underestimation of brown dwarf masses by 20 to 30%. Calibrating these models is necessary as they are also used to infer the masses of young, directly imaged exoplanets such as those found at the VLT.

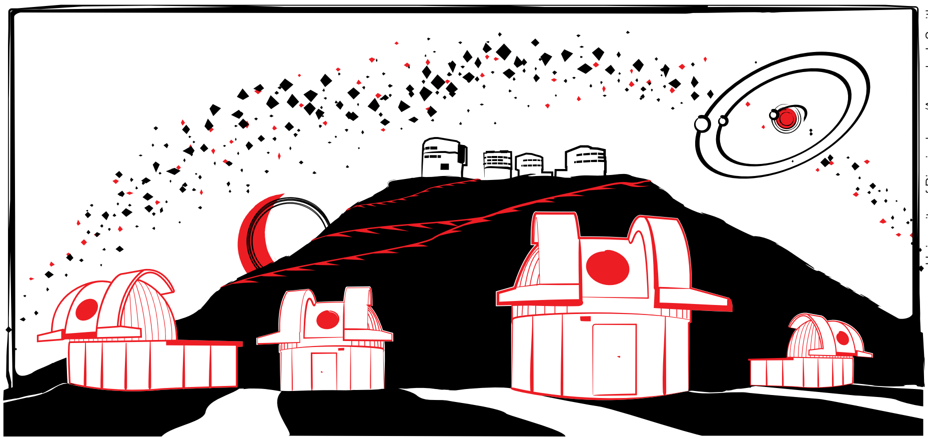
Introduction

Several methods are used to measure the radii of celestial objects. Most generally, astronomers combine parallax, bolometric luminosity and effective temperature and use the Boltzmann law ($L = 4\pi R^2 \sigma T^4$) to determine a radius. For sufficiently bright and nearby systems, or for bright, large stars, interferometry can be used to directly measure stellar discs (for example, Demory et al., 2009). Alternatively, one can use the blocking of starlight during a lunar occultation or an eclipsing binary system to measure size (for example, Torres et al., 2010). Thanks to parallax measurements, radii for millions of stars are already determined from luminosities and temperatures. With Gaia, billions more are being inferred. However, masses cannot be measured for the vast majority of these stars.

The best-established method of measuring the mass of celestial objects is through the gravitational pull of one object on another. This is commonly achieved in co-orbital systems, such as a pair of stars or a satellite orbiting a planet. Using a time series of spectroscopic measurements, one can obtain the line-of-sight velocity along the orbit and obtain a lower limit on mass. If only one star is detected, the mass of its companion can only be inferred by assuming a mass for the detected object. These are called single-line binaries, and include exoplanets detected by the radial-velocity method. If the velocities for both stars are detected, i.e., in double-line binaries, we can directly measure the mass ratio of the pair. In either case, we need to know the orbital inclination of the system with respect to the plane of the sky to obtain the true masses of the objects.

Eclipsing double-line binaries circumvent this restriction by allowing one to measure the inclination angle (even when not entirely edge-on) and hence the true masses. These systems have been used to calibrate stellar models and study the physical properties of stars (for example, Torres et al., 2010). The eclipses themselves permit the measurement of

Figure 1. Illustration of the four SPECULOOS telescopes constructed at Paranal, showing the VLT in the background, a rising moon and a planetary system symbolising our aspirations. The Milky Way arches over the scene, resembling a photometric time series within which there is a planetary transit.



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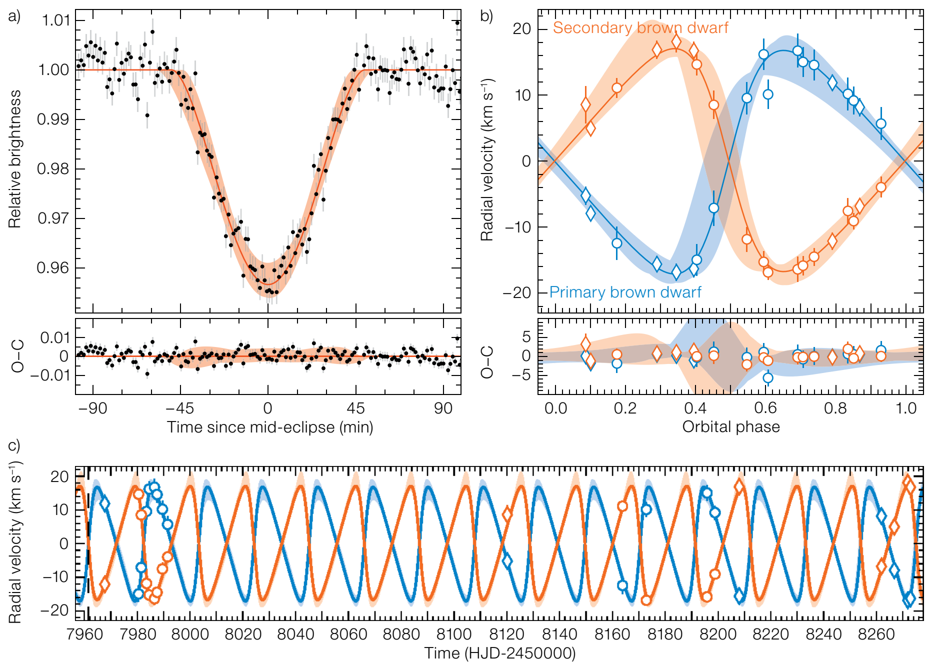

Figure 2. Data confirming the detection of a brown dwarf double-line eclipsing binary (Triaud et al., 2020). (a) Photometric time series obtained during a commissioning run of the SPECULOOS facility at Paranal, showing a 4% deep grazing eclipse. (b) Radial-velocities as a function of orbital phase. Dots represent UVES measurements, while diamonds were obtained with NIRSPEC. (c) Radial velocities as in (b), but as a function of time. The dashed line at day 7961 shows when the eclipse of a) was observed. In all plots, the shaded areas depict the 2-sigma uncertainty about the best fit model. Figure from Triaud et al. (2020).

the relative luminosities of the binary components, a function of their sizes and temperatures. Since temperatures can usually be determined from the same spectra that we collected to measure mass, we can uniquely solve for the masses and radii of the pair.

Age is also a fundamental parameter, particularly for brown dwarfs, as these sources constantly cool and never reach a main sequence (Kumar, 1962; Hayashi & Nakano, 1963; Baraffe et al., 2003). At sufficiently old ages, brown dwarfs can become too cold and dark to be detected; the coldest known brown dwarf to date has a temperature of 250 K (Luhman, 2014). Age cannot generally be determined directly for stars and is instead inferred for Sun-like stars from proxies such as rotation, magnetic activity or kinematics. For brown dwarfs, age can be inferred from evolution models if mass, radius and luminosity are simultaneously known, but such cases are rare. Thankfully, ages for brown dwarfs can be inferred if they are associated and coeval with other stars in wide binaries or stellar clusters and associations. However, it is rare to also be in a position to measure the masses or radii of these brown dwarfs as we do here.

The SPECULOOS project

The goal of the Search for habitable Planets EClipsing ULtra-cOOl Stars project (SPECULOOS[1]) is to look for systems similar to the seven temperate rocky worlds of TRAPPIST-1[2] (Gillon et al., 2017), which was found during a pilot survey with the TRAnsiting Planets and PlanetesImals Small Telescope at Cerro La Silla (TRAPPIST-South). SPECULOOS is based on a constellation of six robotic telescopes. Four of the telescopes are located at ESO's Paranal Observatory, one on el Teide in Tenerife (Spain), and another at San Pedro Mártir in Lower California (Mexico). The telescopes were constructed by the Universities of Birmingham, Cambridge and Bern, the Instituto de Astrofísica de Canarias (IAC) and Massachusetts Institute of Technology (MIT), led by the University of Liège. The collaboration also involves researchers from other institutions, and some observations are obtained with the TRAPPIST telescopes at La Silla and Oukaïmeden (Morocco).

The telescopes all have 1-m-diameter mirrors and deep-depleted back-illuminated CCDs that are able to observe efficiently in the near-infrared. The performance of the telescopes and our main research activities were described in a previous Messenger (Jehin et al., 2018). The four telescopes at Paranal, named after moons of Jupiter (Io, Europa, Ganymede and Callisto) officially initiated their survey for transiting planets in January 2019.

Observational campaign

During the commissioning of Europa, and to test the performance of the telescope and its camera, a brown dwarf called 2MASSW J1510478-281817 (hereafter 2M1510), with an M8 spectral type, was monitored for several nights. This source was chosen for its brightness and location on the sky, reaching the zenith and crossing the meridian near the middle of the night. On the second night of observations, an eclipse with 4% depth was detected with a shape similar to those produced by grazing eclipsing binaries (Figure 2a). Observations obtained during subsequent nights showed the source was photometrically stable, implying that the signal was likely real.

A search of the scientific literature revealed a crucial piece of information. 2M1510A has a known common proper-motion companion (2M1510B) located seven arcseconds away (about 250 au), which too has an M8 spectral type. Interestingly, the companion was noted to be fainter by a factor of two by Gizis (2002) who wrote that "[2M1510A] might be an equal luminosity double," suggesting the presence of a binary system.

Separately, Gagné et al. (2015) proposed that 2M1510 is a member of the young moving group Argus, which contains 35 other stars with an age of 45 ± 5 Myr, a fact that we were able to confirm with our subsequent radial velocity measurements.

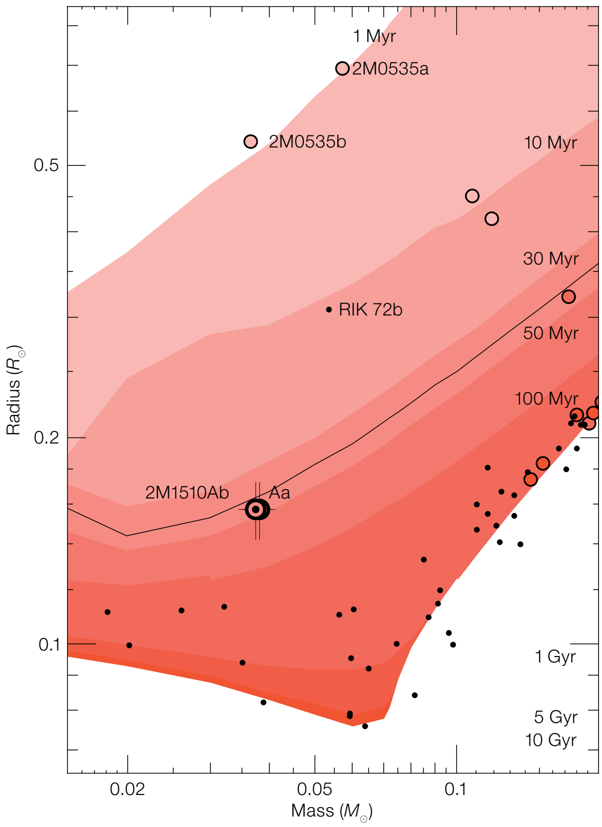

Figure 3. Mass-radius diagram displaying all known mass and radius measurements within this parameter space. Single-line binaries and measurements obtained from interferometry are shown as black dots, while double-line eclipsing binaries are represented as open circles. Three brown dwarf systems are labelled by name, including 2M1510Aab — the system we discovered. The coloured areas represent the Exeter/Lyon evolution models (Baraffe et al., 2003, 2015), with changes in tone corresponding to ages labelled in the diagram. The 40 Myr isochrone is highlighted in black and 2M1510Aa and 2M1510Ab fall between the 40 and 50 Myr isochrones, independently consistent with the age of the Argus moving group. Figure from Triaud et al. (2020).

To verify that 2M1510A was a binary, we first obtained a single spectrum using the near-infrared spectrograph NIRSPEC on Keck II, which showed 2M1510A to be a double-line binary. We then applied for an ESO Director's Discretionary Time (DDT) programme to use the Ultraviolet and Visual Echelle Spectrograph (UVES) on the VLT to monitor the motion of the binary components. Less than three weeks after the eclipse, we were able to determine the orbital period and relative luminosity of the system. The UVES and NIRSPEC data combined revealed a near equal-mass binary on an eccentric 21-day orbit with a timing consistent with the eclipse we had observed (Figures 2b & 2c). We later refined the orbital parameters with further observations with NIRSPEC and UVES. We also monitored the source repeatedly to search for a second eclipse, which eluded us until a partial event was obtained using the Las Cumbres Observatory Global Telescope (LCOGT) 1-m telescope at Siding Springs (Australia), nearly two years after the first event.

Our results

From the radial velocities of the components obtained with UVES and NIRSPEC, and the photometry from SPECULOOS, we found that the two brown dwarfs have almost equal masses of 40 Jupiter masses (within uncertainties). Unfortunately, the current configuration means that only one eclipse is visible, near periastron, when the more massive component (2M1510Aa) of the pair partially covers the less massive component (2M1510Ab). At apastron, their discs do not overlap. This makes it harder to measure radii, since we can only measure the sum of the two radii from the shape of a single eclipse. Fortunately, since both objects have near equal mass and temperature, we can safely assume their radii are similar too, which we measure to be 1.6 times the radius of Jupiter.

By placing the masses and radii on a mass-radius diagram (Figure 3), and comparing them with evolution models from the Exeter/Lyon group (Baraffe et al., 2003, 2015), we find that the system overlaps almost perfectly with a 40 Myr isochrone, close to the age of the Argus Association, validating those models as well as the physics within them at an "evolved" age for the first time.

Interestingly, we do not find as good a match for the luminosities of the system. The Exeter/Lyon models predict absolute magnitudes for 40 Myr-old objects which, correcting for distance and the binary nature of the system, do not match the apparent magnitudes of the components as measured by 2MASS.

Conclusions

Usually, the masses of young brown dwarfs in young associations or co-moving groups are estimated using evolution models, based on their absolute magnitudes, effective temperatures and the age of the group. Following this procedure, we would find a mass for 2M1510A that is 20–30% lower than dynamically measured. The reason for this discrepancy may be linked to the treatment of various opacities in brown dwarf atmospheres, which are sufficiently cool that condensates can form in abundance. Our results suggest that the physics of the evolution models is correct to first order, but that further refinements, such as their atmospheric properties, may be required.

Similar models are routinely used to infer the masses of directly imaged exoplanets, such as those detected with NACO and SPHERE on the VLT. Our work suggests that those mass determinations may have to be revised in the future as evolution models are calibrated with systems like 2M1510A.

Systems with mass, radius, age and luminosity measurements are extremely valuable for calibrating evolution models, which can then be applied to objects that are single, or for which age is hard to determine. In the case of brown dwarfs, however, evolution models lack sufficient calibration. The system we identified is only the second double-line eclipsing brown dwarf system discovered to date. Several single-line binary systems containing brown dwarfs eclipsing main sequence stars have been identified by transiting exoplanet surveys (for example, Hodžić et al., 2019), but characterisation of the brown dwarf depends on the correct characterisation of the primary star. The only other double-line eclipsing brown dwarf known was detected in 2006 (Stassun et al., 2006). This object, called 2M0535, is located in the 1 Myr-old Orion cluster, and its physical properties diverge from models, likely due to the effects of magnetic activity or ongoing accretion. The prevailing thinking is that, at these young ages, models cannot encompass the stochasticity of star formation and the variety of physical processes taking place. At later times the physical properties of these objects should converge with theoretical tracks.

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Links

[1] SPECULOOS website: www.speculoos.earth
[2] TRAPPIST-1 website: www.trappist.one
[3] Astropy: www.astropy.org
[4] NUMPY: www.numpy.org
[5] SCIPY: www.scipy.org
[6] MATPLOTLIB: www.matplotlib.org

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Two of the SPECULOOS telescopes searching for exoplanets around nearby stars and brown dwarfs. The Milky Way stretches over them across the left hand corner of the image.