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Galactic panel

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Towards a better understanding of Very Low Mass Stars

Abstract

Very low-mass stars constitute the vast majority of stars in the Universe and they are amenable to the discovery of terrestrial planets in the habitable zone. However, discrepancies exist between the observed properties of very low-mass stars and stellar models. The key to resolving the discrepancies is the discovery and characterization of very low-mass stars in long-period eclipsing binary systems. Compared to short-period systems, the properties of the secondaries will be relatively unaffected by irradiation and tidal interactions. Such candidate long-period eclipsing binaries are routinely found by our team in NGTS and TESS data when searching for planets. We propose to characterize those systems with precise photometry and spectroscopy and so perform an important test of stellar models.

Observing Blocks

Instrument/Telescope	Req. time	Min. time	1 st Option	2 nd Option
FEROS/MPG 2.2-m	3 nights	2 nights	Any Any	Any Any
Sinistro (imager)/LCOGT 1m	60 hours	30 hours	Any Any	Any Any

Cols

Name	Institution	e-mail	Observer?
David Anderson	OnCL	david.r.anderson@warwick.ac.uk	False
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Joanne Rojas	UCN	joanne.rojas@alumnos.ucn.cl	False

Status of the project

- Past nights: 4
- Future nights: 3
- Long term: False
- Large program: False
- Thesis: False

List of Targets

ID	RA	DEC	Mag
TIC-349576261	07:28:02.428	-63:31:04.165	T=11.5326
TIC-300288448	07:19:59.951	-67:50:00.250	T=12.2836
TIC-300380450	07:24:39.925	-66:19:03.656	T=13.967
TIC-167810285	06:59:16.191	-65:29:07.621	T=12.7872
TIC-349790739	07:33:00.915	-61:30:50.700	T=13.422
TIC-1167538	04:43:59.421	-31:54:23.403	T=10.0127
TIC-300139756	07:14:17.843	-68:13:12.162	T=13.1949
TIC-423785115	04:43:40.742	-26:39:00.935	T=11.2457
TIC-344087362	07:12:43.194	-53:08:53.602	T=10.0801
TIC-308151602	08:40:35.025	-66:33:28.093	T=11.9622

Why very low-mass stars?

Most stars in our galaxy are low-mass and at least 70% of those stars in our Solar neighbourhood are M-type (Henry et al. 2006). Whilst the masses and radii of very low-mass stars (VLMSs; $M_* = 0.08\text{--}0.3 M_\odot$) are difficult to determine for field stars (due to their low brightness), they can be readily determined for components in low-mass eclipsing binary systems (EBLMs). This has revealed discrepancies between some stars’ empirical properties and the predictions of stellar evolution models. For example, VLMSs are sometimes inflated with respect to models by up to 20% (e.g. see von Boetticher et al. 2019, and references therein). Metallicity effects may be responsible (Berger et al. 2006), as may the close proximity to a massive primary: tidal interactions in close binaries are thought to enhance the M-dwarf’s dynamo mechanism, which inhibits core convection and inflates its radius (Mullan & McDonald 2001; Chabrier et al. 2007; Kraus et al. 2011).

Due to their small sizes and low temperatures, VLMSs are good candidates for detecting Earth-sized planets in the habitable zone, which is a goal of space missions such as TESS (Transiting Exoplanet Survey Satellite; Ricker et al. 2015) and PLATO (PLANetary Transits and Oscillations of stars; Rauer et al. 2014). A good understanding of VLMSs is a precursor to characterizing their orbiting planets.

Why long-period EBLMs?

The problem is that most well characterized VLMSs are the secondary components in short-period EBLMs and so they are likely to be affected by their proximity to their massive primaries. Thus, models tuned to short-period EBLMs can not be extrapolated to isolated VLMSs. We must characterize a sample of relatively isolated VLMSs to ensure that we have a good understanding of the properties of VLMSs (and therefore of the properties of their orbiting planets) and to test stellar models in this regime. We can do this by characterizing a population of EBLMs with relatively long orbital periods ($P > 20$ d), which is what we propose to do here in a continuation of the program that we began in 20B. Simplistically, we determine the eclipsing body’s size from an eclipse lightcurve and its mass from the reflex motion of the primary star, as measured from the Doppler shift of spectral lines (Fig. 1).

The opportunity afforded by our searches for long-period giant planets

Most transiting planets discovered to date are in short orbits, where they are heavily influenced by their host stars, because they are more likely to transit and they are easier to detect. To understand the planetary population as a whole, as well as how planets form and evolve, we must discover transiting planets in longer orbits. The TESS mission offers us the opportunity to do just that. During the primary TESS mission, most stars were observed for only 27 days. Hence, single transits were observed of many planets in systems amenable to characterization from the ground; Villanueva et al. (2019) estimated the number to be well over 1000. For some of those systems, second transits are being observed by TESS during its extended mission, however, the number of orbits between the two transits (a gap of ~ 2 yr) is unknown and therefore the orbital periods are very poorly constrained. Such systems make up the bulk of our target list (a sub-sample of which is supplied). Photometric monitoring and radial-velocity (RV) measurements are necessary to measure the orbital periods and to characterize the systems. There are ongoing concerted efforts, led by us and by others, to do just that.

Due to the opportunity afforded by TESS to discover long-period giants and our interest in them, we have largely re-purposed our NGTS facility (Paranal; Wheatley et al. 2018) to recover their orbital periods. For example, we published the discovery of NGTS-11b, a Saturn-mass planet in a 35-day

orbit (Gill et al. 2020c). In the same system, we subsequently discovered an additional planet with a mass similar to that of Neptune and we found evidence of an additional body (observations are ongoing; Anderson et al., in prep).

EBLM eclipse depths are often consistent with planetary transits due to the comparable size of VLMSs and giant planets, and the large brightness ratio means only a single star is evident in a spectrum. Therefore we tend to take two or more spectra before identifying EBLMs (from their large changes in RV) and then discarding them from planet searches. Thus, the discovery of EBLMs is a natural by-product of surveys for transiting planets (such as NGTS). Indeed, we recently published the discovery of a 62-day G7+M5 EBLM system (Gill et al. 2020b), which we identified as a candidate from its TESS lightcurve, and then determined its orbital period using the combination of NGTS and the South African node of the LCOGTN (time awarded via CN2019B-25, PI:Moyano). We then measured RVs around the orbit. We found the radius of the VLMS to be consistent with MESA models of stellar evolution to better than 1σ .

Even with very careful vetting prior to follow-up observations, only 10% of candidates from ground-based transit surveys turn out to be planets. Many of the remainder are eclipsing binaries. Thus searches for long-period giant planets are a rich source of long-period EBLMs. We propose here to conduct further observations of those long-period EBLMs so as to obtain a sample of well characterized, homogeneously studied, and relatively isolated VLMSs for comparison with stellar models.

A program with momentum

We only started this program in 20B and, like everyone, we have been affected by the global pandemic. Despite that, we have made good progress to date. Figure 1 shows the discovery data for one long-period VLMS, which is to be presented alongside another such system in a paper led by PI Moyano. Also, Figure 2 shows two more long-period VLMSs that we only started to observe with FEROS late in semester 20B. With near-real-time reduction and analysis of the data, we were able to target particular phases and to tune the exposure times to make efficient use of our facility time. With some time lost to the Bolivian winter and to the pandemic-related shutdown, it is notable that we were able to almost complete the characterization of two 25-day orbits in less than a month (Figure 2; one may be a rare brown dwarf). We will finish those two systems with a little of our 21B FEROS allocation. A key factor of our success is our membership of the time-share group led by Brahm, which permits us to spread our measurements in time.

References: Berger+ 2006ApJ...644..475B; von Boetticher+ 2019A&A...625A.150V; von Boetticher+ 2017A&A...604L...6V; Boyajian+ 2012ApJ...757..112B; Chabrier+ 2007A&A...472L..17C; Chaturvedi+ 2018AJ....156...27C; Gill+ 2018A&A...612A.111G; Gill+ 2019A&A...626A.119G; Gill+ 2020MNRAS.491.1548G; Gill+ 2020MNRAS.495.2713G; Gill+ 2020ApJ...898L..11G; Chew+ 2014A&A...572A..50G; Henry+ 2006AJ....132.2360H; Kraus+ 2011ApJ...728...48K; Moyano+ 2017MNRAS.471..650M; Mullan & MacDonald 2001ApJ...559..353M; Pollacco+ 2006PASP..118.1407P; Rauer+ 2014ExA....38..249R; Ricker+ 2015JATIS...1a4003R; Triaud+ 2013A&A...549A..18T; Triaud+ 2017A&A...608A.129T; Villaneuva+ 2019AJ....157...84V; Wheatley+ 2018MNRAS.475.4476W;

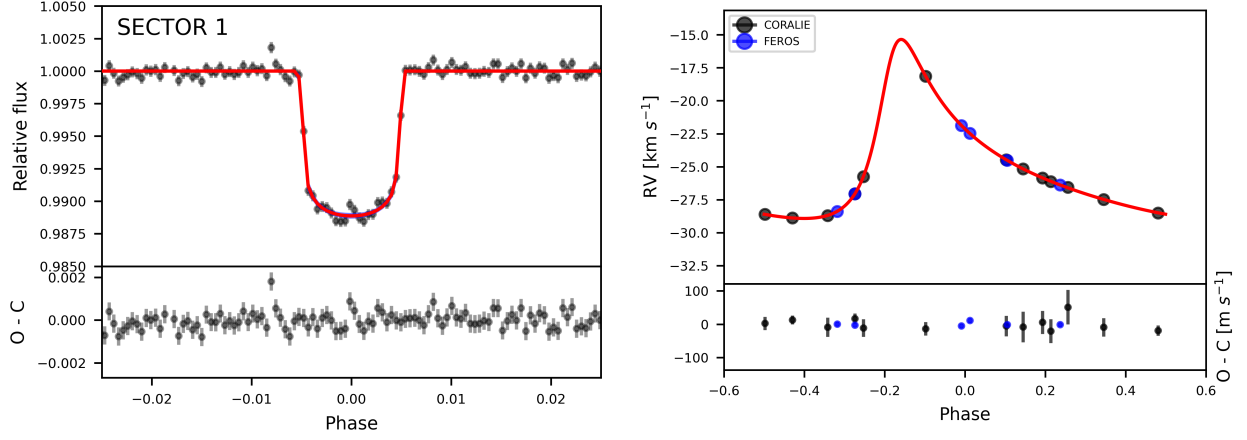


Figure 1: Our discovery of a VLMS ($M_2 = 0.104 \pm 0.002 M_\odot$) in a 44.9-d orbit around the Sun-like star TIC-159730525 (Moyano et al., in prep.). **(Left)** The TESS eclipse lightcurve. **(Right)** The reflex motion of the primary due to the secondary, illustrated by our radial velocities, which we phase-folded on the best-fitting ephemeris. We determined the orbital period from a combination NGTS photometry and radial velocities.

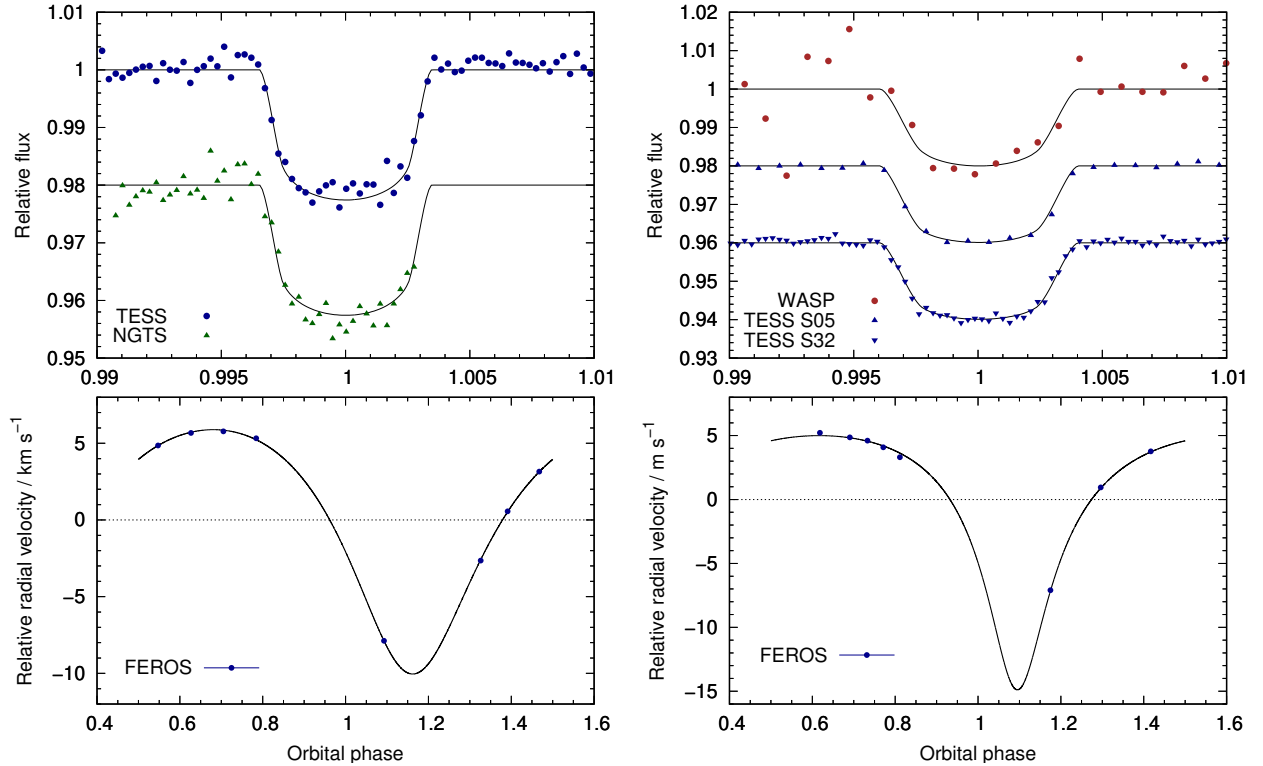


Figure 2: **(Left)** Our discovery of a VLMS near the hydrogen-burning limit in a 25.4-day orbit around TIC-300139756. We characterized the system using transit lightcurves from TESS and NGTS (top panel; offset for display) and relative radial velocities from FEROS (bottom panel; CN2020B-56, PI:Moyano). **(Right)** Our discovery of a brown dwarf or VLMS in a 24.7-day orbit around TIC-423785115. We characterized the system using transit lightcurves from TESS and WASP (top panel; offset for display) and relative radial velocities from FEROS (bottom panel; CN2020B-56, PI:Moyano).

CURRENT STATUS OF THE PROJECT

The discovery of EBLMs is a natural by-product of surveys for transiting planets such as the Chilean search for warm Jupiters (TESS-CL; Co-Is: Brahm, Jenkins, Jordán, Moyano, Vines) and the Next Generation Transit Survey (NGTS; Co-Is: Anderson, Gill, Jenkins, Jordán, Moyano, Vines). Members of these teams have been active in publishing such systems, e.g. Triaud et al. (2013, 2017), Chew et al. (2014), von Boetticher et al. (2017, 2019), and Gill et al. (2019, 2020a, 2020b). Recently, these groups have joined forces to share their expertise and to coordinate efforts. This has already produced results, with the publication of a 62-day G7+M5 EBLM (Gill et al. 2020b) and a Saturn-mass planet in a 35-day orbit (Gill et al. 2020c). We draw our targets from those surveys and some of our targets already have some follow-up lightcurves and radial velocities.

With our CNTAC awards in 20B and 21A, we confirmed and characterized both planets and long-period VLMSs (observations and analyses are ongoing; some results are shown in Figs. 1 & 2). For example, despite the understandable disruption caused by Covid-19 to operations at La Silla, we were able to begin observing two candidate warm Jupiters, determine that they were VLMSs, and almost finish characterizing the systems. Just a few more FEROS measurements at key phases are required to publish the systems (we are obtaining those in 21B; Fig. 2).

PI Moyano has experience in solving these long-period systems. We discovered two VLMSs, first detecting eclipses in TESS and subsequently fully characterizing the systems with the combination of NGTS, CORALIE and FEROS. One of those systems (TIC-159730525; Fig. 1) is one of the lowest-mass stars ever discovered ($M = 0.104 \pm 0.002 M_{\odot}$; near the hydrogen burning-limit) and, uniquely, is in a wide orbit ($P44.9$ d). Thus, we have demonstrated our ability to detect, confirm and characterize the long-period VLMS systems that are the subject of this proposal. These results will be submitted for publication during 2021B. This program is also serving as the basis of the theses of two current UCN undergraduates (co-Is Vega and Sepulveda) and two new future UCN undergraduate (co-Is Carrasco and Rojas). They are supervised by PI Moyano and co-supervised by co-I Anderson.

TECHNICAL DESCRIPTION

Targets: Our dynamic target list is populated from a variety of warm-Jupiter programs: the warm giant program of Brahm, Jordán et al. (primarily FEROS); the warm giant program of Ulmer-Moll/Bouchy et al. (primarily HARPS); and the NGTS warm giant program. For the majority of our targets, TESS observed two transits separated by ~ 2 years (with no coverage in between). Thus, we must determine which of the ~ 40 candidate periods is correct and we do that cheaply using ground-based photometry (Cooke+ 2021MNRAS.500.5088C). We then rapidly determine the nature of the secondary body (planetary or stellar, with a couple of spectra at quadrature) and efficiently determine its mass and orbital eccentricity (with spectra across the orbit).

Primarily, we exclude period aliases using our 12 NGTS imaging telescopes, however, longitudinal coverage is vital to efficiently solve systems. For any one target, there are some periods (of tens to a few hundred days) with little or no observability in a single season from the NGTS site (Paranal). That is particularly true for pathological periods (e.g. those near integer days), which may not be observable by NGTS for some years. **To efficiently determine systems' true periods, we therefore require access to facilities (LCOGTN) at other longitudes (South Africa and Australia).**

NGTS: The NGTS facility is an array of small, robotic imaging telescopes located at Paranal (Wheatley+ 2018MNRAS.475.4476W). We routinely achieve photometric precision of 150 ppm, which is unprecedented for a wide-field ground-based facility (West et al., 2019MNRAS.486.5094W). We are dedicating the vast majority of NGTS time to determine the orbital periods of candidate long-period planets (and therefore EBLMs too) first detected by TESS. When a candidate period is uncovered by the NGTS observation of a third eclipse, we conduct targeted photometric and RV observations to determine the true period and to characterize the system (Gill et al. 2020c).

LCOGTN: With so many, and such long, candidate orbital periods, 24-hour access to our targets is vital to avoid missing eclipse windows from the NGTS site. With a modest allocation on LCOGTN, we are able to observe tricky periods from South Africa and Australia, as well as to observe from Tololo in the small few instances that the weather is poor at Paranal during an eclipse window. We use the Sinistro imagers on the 1-m telescopes of the LCOGTN to rule out those candidate periods that are difficult or impossible to rule out with NGTS, and to observe a second eclipse when we are sure of the true orbital period. During each eclipse window, we take a time-series of images through a red filter (to minimise the effects of limb darkening), with exposure times tuned to the brightness of the target, and a small defocus (to minimise the effects of flat-fielding errors and to increase the duty cycle). Typical observation durations of (partial) eclipses are 5 hr. With 60 hr we will thus be able to observe ~ 12 eclipse windows. **To enable us to target specific windows we request time-critical status.**

FEROS: Once we have determined a system's orbital period from photometry, we take spectra at quadrature (orbital phases of 0.25 and 0.75) to determine the nature of the secondary body. For a low-mass stellar secondary body, we then measure radial velocities (RVs) across its phase curve so as to determine its mass and orbital eccentricity. For planetary candidates (i.e. those showing little or no motion from our first two RVs), we pass the candidates to our warm giant programs, which mostly use FEROS. Instrument continuity permits the reconnaissance data to be combined with the subsequent additional data that are taken to fully characterize the system.

Estimating a need for a total of 10 RVs per system, with typical exposure times of 15 min (+3 min overhead), that leads to a total request of 3n to characterize up to 10 systems. We employ the observing and reduction strategy of Jordán et al. (2020AJ....159..145J). To efficiently schedule the observations, we pool awarded time with the time-share group coordinated by Brahm.