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## CN2023A-82

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 | 4 nights | 2 nights | Any Any | Any Any |
| Sinistro (imager)/LCOGT 1m | 80 hours | 40 hours | Any Any | Any Any |

## CoIs

| Name | Institution | e-mail | Observer? |
|---|---|---|---|
| David Anderson | OnCL | david.r.anderson@warwick.ac.uk | False |
| Jose Vines | UCH | jose.vines.l@gmail.com | True |
| Andres Jordan | UAI | andres.jordan@uai.cl | False |
| Rafael Brahm | UAI | rbrahm@gmail.com | False |
| James Jenkins | UDP | james.jenkins@mail.udp.cl | False |
| Francisca Sepulveda | UCN | francisca.sepulveda@alumnos.ucn.c | False |
| Macarena Vega | OnCL | m.vega.pallauta@gmail.com | False |

## Status of the project

- Past nights: 10
- Future nights: 0
- 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 |

SCIENTIFIC AIM AND RATIONALE

**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 cannot 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 ($P > 20\,\mathrm{d}$), which is what we propose to do here in a continuation of the program that we began in 2020B. 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 $\sim$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 $1\sigma$.

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 2020B 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 presented alongside another such system in a paper led by PI Moyano (submitted). 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). We are completing the characterization of those two systems with FEROS during 22B. A key factor of our success is our membership of the time-share group led by Brahm/Hobson, 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; Gill+ 2022MNRAS.tmp..844G; Chew+ 2014A&A...572A..50G; Henry+ 2006AJ....132.2360H; Kraus+ 2011ApJ...728...48K; Moyano+ 2017MNRAS.471..650M; Moyano+ submitted; 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;

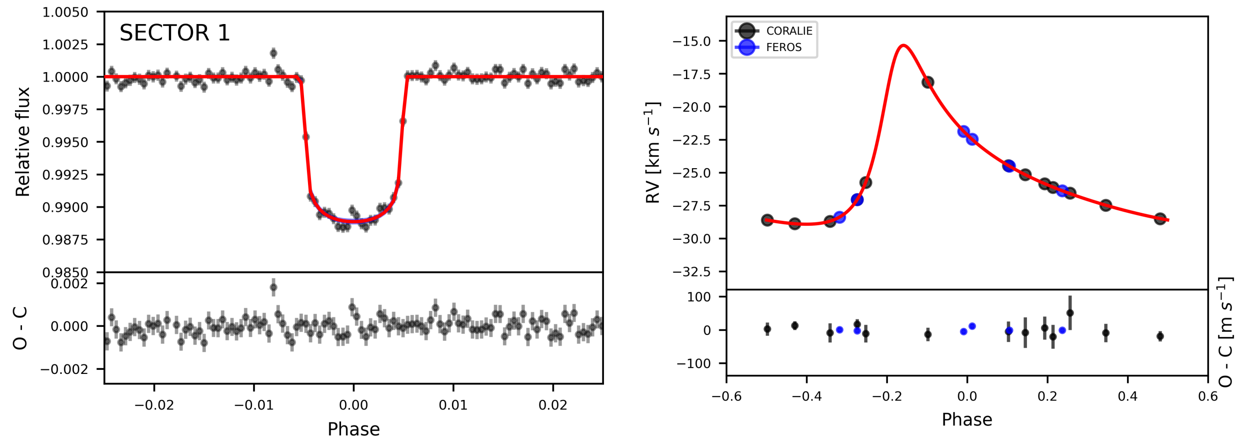


Figure 1: Our discovery of a VLMS ($M_2 = 0.104 \pm 0.002\, M_\odot$) in a 44.9-d orbit around the Sun-like star TIC-159730525 (Moyano et al., submitted). **(Left)** The single eclipse in the TESS lighcurve. **(Right)** The reflex motion of the primary due to the secondary, illustrated by our radial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

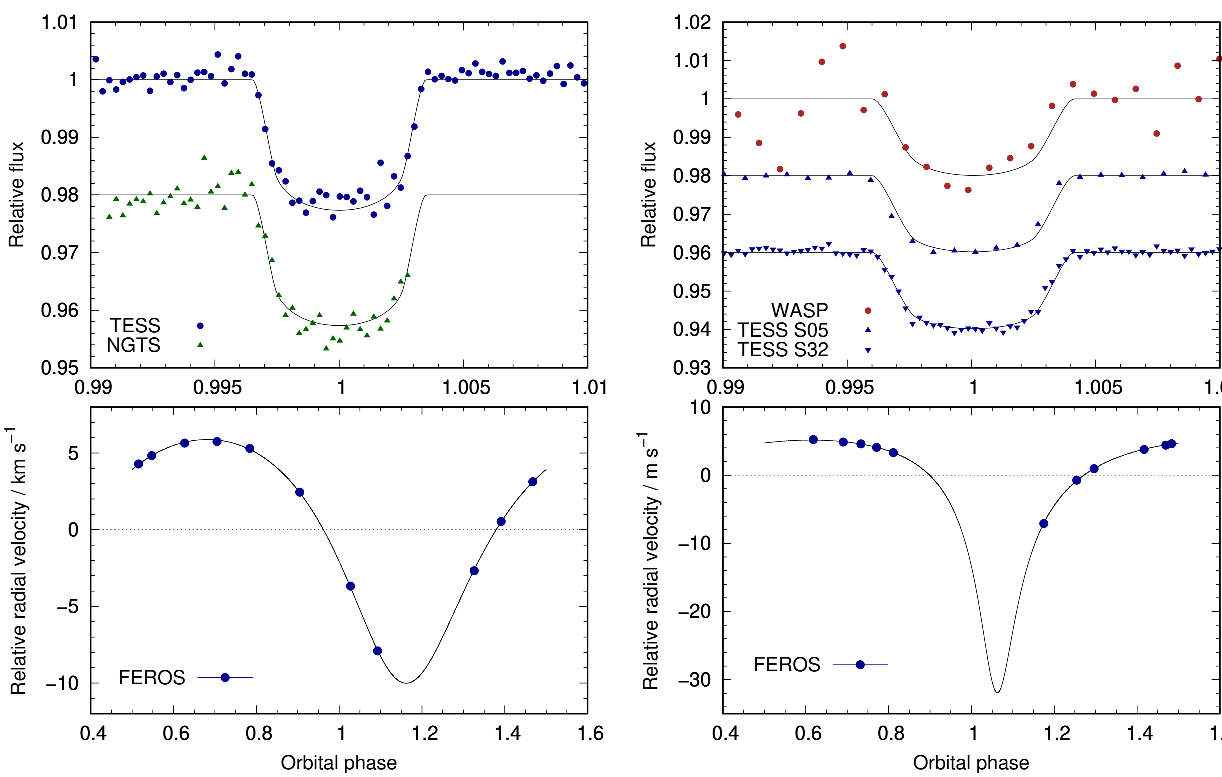


Figure 2: Updated for 22B. **(Left)** Our discovery of a VLMS near the hydrogen-burning limit in a 25.4-day orbit around TIC-300139756. We characterized the system using transit lightcurves from TESS and NGTS (top panel; offset for display) and relative radial velocities from FEROS (bottom panel); we are finishing off this target with our 22B allocation. **(Right)** Our discovery of a VLMS in a 24.7-day eccentric orbit around TIC-423785115. With our time in 22B, we will observe phases 0.8 to 1.2, which are vital to measure the orbital eccentricity and the mass of the secondary in this system.

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, 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). These groups have joined forces to share their expertise and to coordinate efforts. This is proving very fruitful, with the publication of a 62-day G7+M5 EBLM (Gill et al. 2020b), a Saturn-mass planet in a 35-day orbit (Gill et al. 2020c), an 29.8-day M-dwarf close to the hydrogen-burning limit (Gill et al. 2022) and two additional VLMSs close to the hydrogen-burning limit (Moyano et al. submitted). We draw our targets from those surveys and some of our targets already have some follow-up light curves and radial velocities.

We began this project in 20B and, despite the challenges of the pandemic, bad weather and technical issues, we are making rapid and efficient progress. Of the 13 targets that we have observed to date, 8 are looking to be EBLMs, 4 are looking to be planets and 1 was a false positive (a blend). Three of our VLMS discoveries are shown in Fig. 1 (submitted) and Fig. 2 (to be finished in 22A and 22B). We have less data on the other systems; our time in 22B and time in 23A are vital to complete their characterization. Notable within that list is an EBLM, TIC-300288448, whose orbital period we confirmed to be 107.6 d from photometry and whose mass and orbital eccentricity we are currently measuring with FEROS (3 points to date). TIC-300288448 will be the longest-period EBLM with an accurate determination of the radius and mass of the secondary. We published the longest known EBLM to date (TIC-231005575; P= 61.8 d; Gill et al. 2020b).

We recently completed a search of all southern-hemisphere TESS-SPOC light curves taken to date and we are in the process of selecting more candidates from those. One notable new target, TIC-149625812, is an EBLM ($R_2 \approx 0.2 R_\odot$) in either a 356-d or 713-d orbit. With LCOGTN photometry and FEROS spectroscopy, we will confirm and characterize that system and thus push the envelope of well-characterized EBLMs much farther.

PI Moyano recently submitted a paper announcing the discovery and characterization of two long-period EBLMs. We first detected the eclipses in TESS lightcurves and subsequently fully characterized the systems with the combination of NGTS 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 ($P = 44.9\,\mathrm{d}$). Thus, we have demonstrated our ability to detect, confirm, characterize and publish the long-period EBLM systems that are the subject of this proposal.

This program has already served as the basis of the theses of two UCN undergraduates (Co-Is Vega and Sepulveda), who passed their oral defences in March of 2022, and it will be the thesis topic for two future UCN undergraduates. The students are supervised by PI Moyano and co-supervised by Co-I Anderson. Given the success of her thesis, Co-I Vega was accepted in the Master in Astrophysics and Space Science program of the University of Rome Tor Vergata.

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 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 (long periods and those near integer days), which may not be observable by NGTS for 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 80 hr we will thus be able to observe ∼16 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 4 n to characterize up to 13 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 co-I Brahm.