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Galactic panel
Maximiliano Moyano | mmoyano@ucn.cl
UCN
faculty

Towards a better understanding of Very Low Mass Stars

Abstract

Very low mass stars constitute the vast majority of stars in the Universe. However discrepancies exist between the observed properties of these stars and stellar models. The key to understanding these discrepancies is to find and characterise very low mass stars in eclipsing binary systems. To test and refine the stellar models we need to find long-period eclipsing binaries, where the stellar properties are not effected by irradiation or tidal interactions. Such long-period eclipsing binaries are being found by our team in NGTS and TESS data, and this proposal will capitalise on these discoveries by characterising these systems with high precision photometry and spectroscopy.

Observing Blocks

Instrument/Telescope	Req. time	Min. time	1^{st} Option	2^{nd} Option
FEROS/MPG 2.2-m	2 nights	1 nights	Any Any	Any Any
CHIRON/SMARTS 1.5-m	20 hours	10 hours	Any Any	Any Any
Sinistro (imager)/LCOGT 1m	40 hours	20 hours	Any Any	Any Any

CoIs

Name	Institution	e-mail	Observer?
David Anderson	OnCL	david.r.anderson@warwick.ac.uk	True
Rafael Brahm	UAI	rbrahm@gmail.com	False
Andres Jordan	UAI	andres.jordan@uai.cl	False
James Jenkins	UCH	jjenkins@das.uchile.cl	False
Samuel Gill	OnCL	samuel.gill@warwick.ac.uk	False
Jose Vines	UCH	jose.vines.l@gmail.com	True

Status of the project

- Past nights: 0
- Future nights: 9
- Long term: False
- Large program: False
- Thesis: False

List of Targets

ID	RA	DEC	Mag
TIC-278536652	22:11:09.8818	-39:09:17.75	T=10.3
TIC-410450228	7:51:34.7957	-60:24:44.7773	T=10.7; 4FEROS
TIC-453060368	9:43:35.3731	0:36:53.9332	T=12.8; 2FEROS
TIC-454718065	11:40:07.4421	-74:44:49.5445	T=10.1; 3FEROS
TIC-165493409	12:01:46.873	-36:26:48.9619	T=10.4; 2FEROS
TIC-355425863	0:05:38.0589	-53:45:55.9065	T=11.5; 4FEROS
TIC-166671025	2:17:36.8694	-52:52:04.0298	T=12.4; 6FEROS
TIC-31656385	3:06:38.2847	-66:00:28.7384	T=11.9; 6FEROS
TIC-140760434	4:56:31.2581	-74:55:13.6042	T=10.8; 3FEROS
TIC-13064883	5:03:14.7821	-25:22:41.4977	T=9.5; 2FEROS
TIC-55383975	5:09:32.0434	-64:01:34.3032	T=11.3; 4FEROS
TIC-72556406	6:14:07.0025	-8:03:44.3059	T=10.8; 5FEROS
TIC-469967533	23:55:26.0173	-54:29:41.819	T=12.7; 4FEROS
TIC-399144800	10:52:47.9873	-67:23:16.1324	T=10.6; 3FEROS

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 (VLMS; $M_* = 0.08$–$0.5\,M_\odot$) 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, VLMS 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).

A good understanding of VLMS is a precursor to characterising their orbiting planets. Due to their small sizes and low temperatures, VLMS 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).

Why long-period EBLMs?

The problem is that, to date, most well characterised VLMS are the secondary components in short-period EBLMs and so they are likely to be affected by their proximity to their massive primaries (Figure 1, left). This means that we can not extrapolate models that have been tuned to short-period EBLMs to isolated VLMS. We must characterise a sample of relatively isolated VLMS to ensure that we have a good understanding of their properties (and therefore of the properties of their orbiting planets) and to test stellar models in this regime. We can do this by characterising a population of EBLMs with relatively long orbital periods ($P > 25\,\mathrm{d}$), which is what we propose to do here.

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 nominal TESS mission, most stars will be observed for only 27 days. Hence, Villanueva et al. (2019) estimate that single transits will be detected from well over 1000 planets orbiting stars amenable to characterisation from the ground. Although additional transits will later be observed by TESS, during its extended mission, the number of epochs elapsed between the two transits will be unknown and therefore the orbital period will be very poorly constrained. Thus photometric monitoring and radial-velocity measurements are necessary to measure the orbital periods and to characterise 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 the orbital periods of those candidate long-period transiting planets that we identify from TESS data. Indeed, we are publishing the first ever discovery of a planet that was initially identified from a TESS single-transit event (Figure 2, left; NGTS-11b; a Saturn-mass planet in a 35-day orbit; Gill et al. 2020c).

EBLM eclipse depths are often consistent with planetary transits due to the comparable size of VLMS 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 radial velocity) 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). Likewise, the discovery of long-period EBLMs is a natural by-product of surveys for long-period transiting planets. Indeed, we recently published the discovery of a 62-day G7+M5 EBLM system (Gill et al. 2020b), which was the first time that the orbital period of a TESS single-transit object was recovered by a subsequent blind photometric survey. After identifying the system as a candidate long-period giant planet, we caught the second eclipse with NGTS and the third eclipse with the South African node of the LCOGTN (time awarded via CNTAC:CN2019B-25, PI:Moyano), and we measured radial velocities around the orbit (Figure 2, right). 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 turned out to be planets. Many of the remainder were 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 characterised, homogeneously studied, and relatively isolated VLMS for comparison with stellar models.

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+ 2020arXiv200209311G; Gill+ 2020arXiv200500006G; 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;

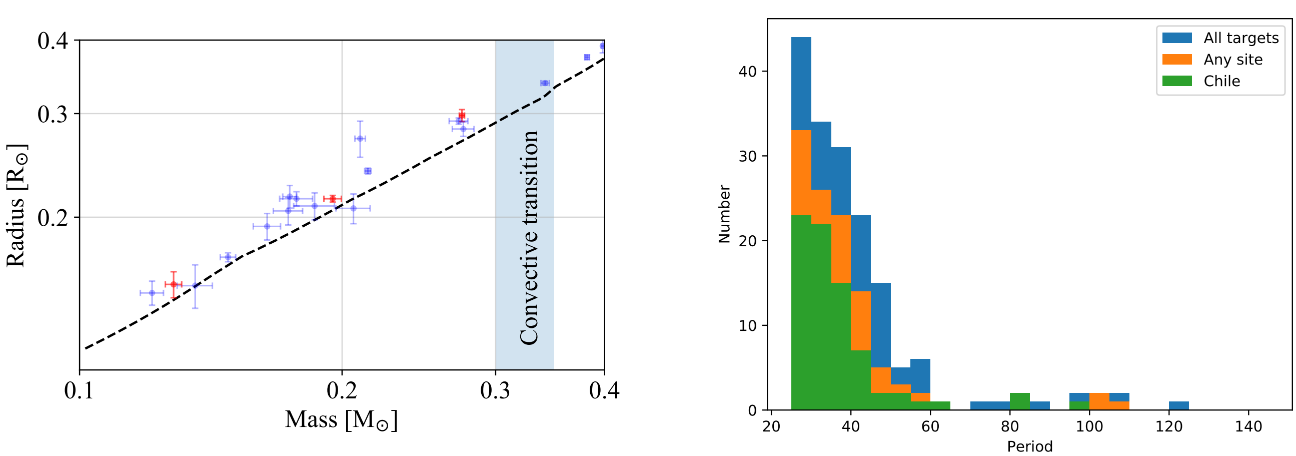

Figure 1: **(Left)** The mass-radius distribution for well characterised eclipsing VLMS (uncertainties less than 10%) that are well separated ($P > 25$ d; red) and in close-in orbits ($P < 25$ d; blue). **(Right)** We predicted the yield of single-transit planets from TESS (blue) and tested whether a transit is observable within a 100-day period from any southern LCOGTN site (orange) or from Chile (green). While many would be observable from Chile, longitudinal coverage offers a clear benefit to the recovery of long-period systems.

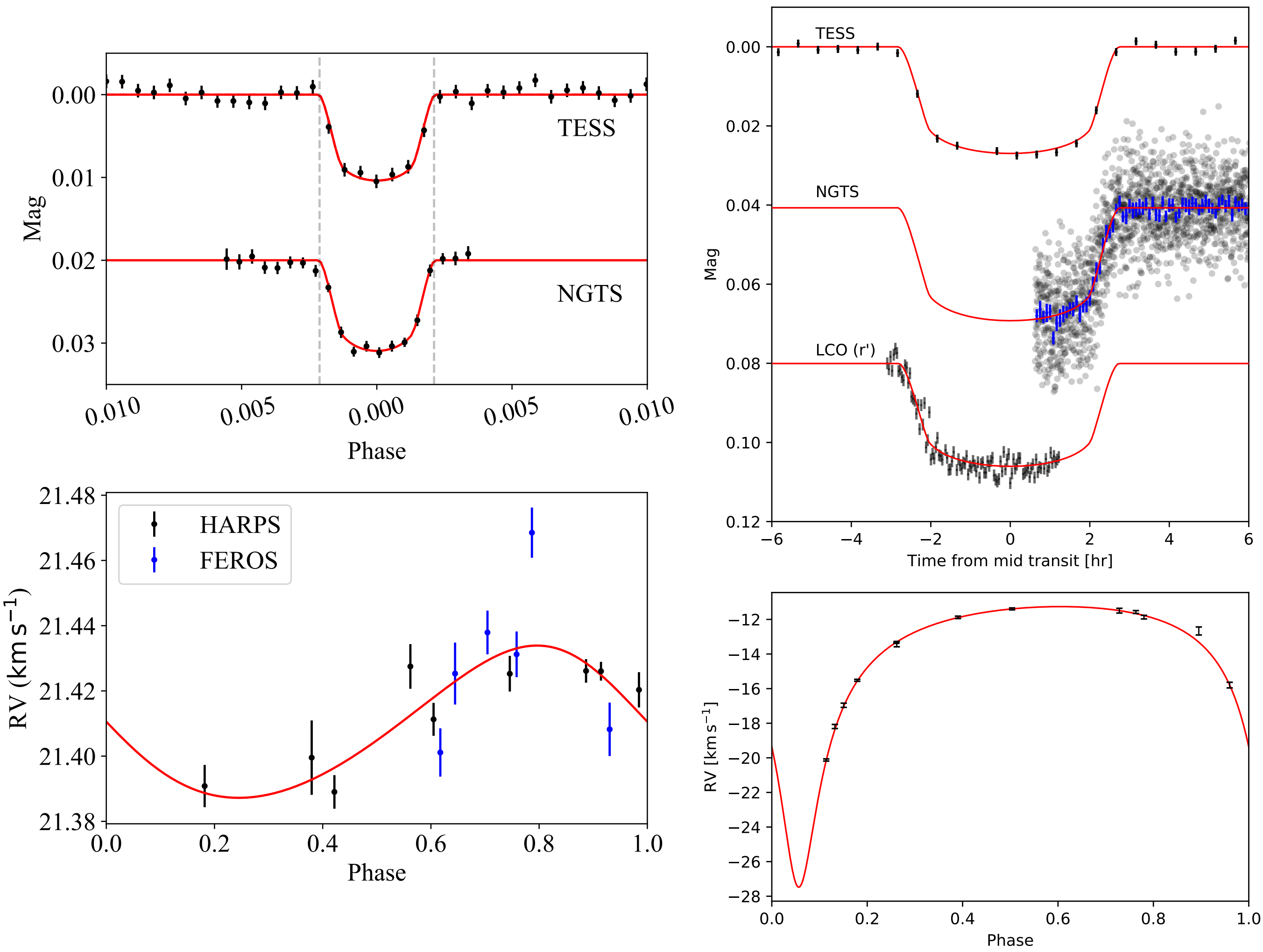

Figure 2: **(Left)** Transit lightcurves (top panel; offset for display) and radial velocities (bottom panel) of the 35-day transiting warm Saturn NGTS-11b (Gill et al. 2020b). Most RVs were taken at high airmass as the target was setting. Without the HARPS points, a factor of 2–3 times the amount of FEROS points (a total of ∼15) would have been sufficient on their own to characterise the system. The data are from FEROS (CNTAC:0104.A-9012; PI:Vines; Opticon:2019A/037, PI:Bayliss) and HARPS (ESO:0104.C-0413, PI:Brahm; ESO:0104.C-0588, PI:Bouchy). This indicates the strength of our collaboration. **(Right)** Primary eclipse photometry (top panel; offset for display) and radial velocities (bottom panel) of the 62-day G7+M5 EBLM system TIC-231005575 (Gill et al. 2020a). The data from LCOGTN (South Africa) were vital in the discovery (CNTAC:CN2019B-25, 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 is already producing results, with the publication of a Saturn-mass planet in a 35-day orbit (Gill et al. 2020c).

The TESS Science Office (TSO) releases around 80 TOIs (TESS Objects of Interest) per sector, comprising planet candidates, single-transit planet candidates, and other timely targets of opportunity. Using our wealth of experience with ground-based transit surveys (WASP, HAT-S, NGTS), we are independently extracting light curves from the TESS full-frame images and searching them for long-period planet candidates, including those with single transits. Two subsets of our team (one sub-team is led by Brahm and the other sub-team is led by Gill) are doing this independently and comparing results. This proposal represents our first formal coordinated effort to pursue these systems.

We find many good candidates missed by the TSO. For example, we discovered a 62-day G7+M5 EBLM (Gill et al. 2020b) and a 35-day transiting Saturn (Gill et al. 2020c) after, in each case, first detecting a single transit in our TESS lightcurve. In neither case had the TSO identified the object as a TOI. Thus our team has a proven track record in identifying, characterising and publishing both long-period transiting planets and long-period EBLMs from TESS data.

We have ongoing programs to discover and characterise the planets. Here we are requesting facility time for a new project: we want to make a concerted effort to discover and characterise the long-period EBLMs. Much of the success of the WASP, NGTS and HAT-S exoplanet surveys can be attributed to their custom tools for identifying and tracking candidates. This project taps those resources as well as a new tool (database and portal) designed specifically for this project by Co-Is Anderson and Gill.

We acknowledge that the expertise of PI Moyano is in transiting planets (e.g. Moyano et al. 2017) rather than in low-mass stars, though the analysis techniques are very similar and Co-I Gill is an expert in both EBLMs (e.g. 2019, 2020a, 2020b) and in spectral analysis (e.g. 2018). This program will form the basis of a knowledge-transfer process in which Gill will work closely with Moyano. This joint effort will be the subject of a funding proposal (in preparation) that will support this ongoing collaboration (though the success of this project is not contingent on the award of additional funds). This project will serve as the basis of a thesis of a UCN gradudate student supervised by Moyano and co-supervised by Gill+Anderson.

This proposal leverages the existing Chilean involvement in NGTS by enabling Chilean researchers to take advantage of a valuable by-product of exoplanet hunting, namely the discovery of well characterised low-mass stars.

TECHNICAL DESCRIPTION

Targets: Our targets list, which is growing all the time, comes from a variety of sources, including: the CNTAC warm giant Large Program of Brahm, Jordán et al.; the ESO/HARPS warm giant Large Program of Bouchy et al.; and the NGTS warm giant program of Gill et al. It includes targets with FEROS RVs that are already indicative of long-period EBLMs. The bulk of our facility time comes from NGTS, of which PI Moyano and Co-Is Jenkins, Jordán, and Vines are Chilean members. We request here time on the CHIRON and FEROS spectrographs to perform spectral characterisation of the primary stars and to measure radial velocities (RVs) across the orbits, both to help determine the orbital periods and to measure the masses of the secondaries (the candidate VLMS). We request time on the LCOGTN imagers, which offer good longitudinal coverage (South Africa and Australia), to observe second eclipses when the long periods make that impossible from NGTS in Chile.

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 second eclipse, we will conduct targeted photometric and RV observations to determine the true period and to characterise the system (Gill et al. 2020c).

LCOGTN: Although photometry from a single site (i.e. NGTS at Paranal) is able to observe a second eclipse of a large fraction of systems, there is a clear benefit from longitudinal coverage (Figure 1, right). We will use the Sinistro imagers on the 1-m telescopes of the LCOGTN to observe a second eclipse when we are already fairly sure of the period, or to rule out those possible periods that would otherwise be hard to rule out with either NGTS or RVs. During each eclipse window, we will take a time-series of images through an r' 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 will be 5 hr. With 40 hr we will thus be able to observe $\sim$8 eclipse windows.

CHIRON: We will use CHIRON to obtain RVs of those targets without any RVs to date. We will tune our exposure time to the brightness of the object (typically 15 min). We will employ the observing and reduction strategy of Jordán et al. (2020AJ....159..145J). Recovering the period and sampling the orbit of a long-period EBLM requires around a dozen RVs, so 3 hr per system. Thus to vet 10–15 systems (1–2 spectra each) and to fully characterise 5 systems, we require 20 hr. Vetted candidates with RV variations consistent with planetary companions will be passed to the associated programs.

FEROS: Whilst FEROS is not strictly necessary to characterise moderately bright EBLMs, a number of our targets already have FEROS RVs (details in the List of Targets table, in which TESS magnitude, T, is similar to visible magnitude, V). Observing those targets with another spectrograph (i.e. CHIRON) would require the fitting of an instrumental offset and so would be inefficient. Thus we request time on FEROS to finish off those targets that already have FEROS data. Estimating a need for a total of 10 RVs per system, with typical exposure times of 10 min, that leads to a total request of 16 hr. We will employ the observing and reduction strategy of Jordán et al. (2020AJ....159..145J). In order to schedule our observations, we will share time with the programs of Brahm et al. (10 n/semester) and Jenkins et al. (8 n/semester) and, if necessary, with other programs.