Radial velocity studies of cool stars

Hugh R. A. Jones¹, John Barnes¹, Mikko Tuomi¹,², James S. Jenkins¹,³ and Guillem Anglada-Escude⁴

¹Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK
²Department of Physics and Astronomy, University of Turku, Turula Observatory, Väisäläntie 20, FI-21500 Piikkiö, Finland
³Departamento de Astronomía, Universidad de Chile, Camino del Observatorio 1515, Las Condes, Santiago, Chile
⁴Astronomy Unit, School of Mathematical Sciences, Queen Mary University of London, London E1 4NS, UK

Our current view of exoplanets is one derived primarily from solar-like stars with a strong focus on understanding our Solar System. Our knowledge about the properties of exoplanets around the dominant stellar population by number, the so-called low-mass stars or M dwarfs, is much more cursory. Based on radial velocity discoveries, we find that the semi-major axis distribution of M dwarf planets appears to be broadly similar to those around more massive stars and thus formation and migration processes might be similar to heavier stars. However, we find that the mass of M dwarf planets is relatively much lower than the expected mass dependency based on stellar mass and thus infer that planet formation efficiency around low-mass stars is relatively impaired. We consider techniques to overcome the practical issue of obtaining good quality radial velocity data for M dwarfs despite their faintness and sustained activity and emphasize (i) the wavelength sensitivity of radial velocity signals, (ii) the combination of radial velocity data from different experiments for robust detection of small amplitude signals, and (iii) the selection of targets and radial velocity interpretation of late-type M dwarfs should consider Hα behaviour.

1. Introduction

Over the past two decades, the field of exoplanets has made extraordinary progress. Rather than wondering
about planets beyond the Solar System it is now apparent that stars do normally seem to have planets with a very wide range of properties but that the architecture of the Solar System is not so common [1]. However, this view is one derived from solar-like stars. The search for extrasolar planets (hereafter exoplanets) has been building in intensity since the discovery of HD114762b by Latham et al. [2] and has been driven by a usually healthy competition between different research groups and techniques. Although exoplanets have been discovered around a very wide range of objects [3] and in many different environments, most resources have been dedicated to solar-type stars. This has arisen for a number of major reasons; in particular, it has been convenient that search techniques have had the greatest sensitivity to planets around solar-like stars. The range of different-mass stars where planets have been found and their orbital distances can be seen in figure 1. The predominance of planets around solar-type stars has probably helped the field to draw in significant numbers of researchers from related disciplines. These contribute towards the richness of the field and the range of scientific goals being considered.

Here, we focus on the detection of planets around cool stars, specifically M dwarfs—stars defined as having molecules in their atmospheres and having a mass range of around 0.07–0.5 $M_{\text{Sun}}$. Despite being the most abundant stars in our neighbourhood, relatively few exoplanets have been found and only around the hottest M dwarfs. In this work, we consider only those stars with radial velocity measurements. These radial velocity measurements have been the dominant discovery technique and cover a wide range of semi-major axes, though it should be noted that a number of interesting discoveries made by other techniques are not considered. Although nearby bright ‘solar-like’ stars, such as $\alpha$ Cen [4] and $\tau$ Ceti [5], have many thousands of radial velocity observations with multiple telescopes, even prominent M dwarfs, such as Proxima Cen (the closest star) and Barnard’s star (the star with the greatest motion on the sky), have only a few hundred measurements. The impact of this is that only a few tens of M dwarf planets comprise the approximately 600 stars with radial velocity shown in figure 2 (we note the literature databases: exoplanets.org curated by Wright et al. [6] and exoplanet.eu curated by Schneider et al. [7]).

Figure 1. The plot shows median $M_{\text{star,\odot}}$ values for exoplanet host stars against the semi-major axis of their exoplanets (based on all exoplanets with radial velocity from exoplanets.org—approx. 70% of them were found first from radial velocity data). The upper plot shows all published exoplanets included in the exoplanets.org orbits database as inferred from radial velocities, and the lower plot is a binned version, which indicates median $M_{\text{star,\odot}}$ values; the dashed line represents the sub-sample of all hosts with a planet that has a minimum mass above 1 $M_{\text{Jup}}$ sin $i$. The error bars are from $\sqrt{\text{number}}$ statistics and are only indicative.
Figure 2. For known planet-hosting stars selected as per figure 1, the upper plot shows planet mass ($M_{\text{Jup}}$) versus stellar mass ($M_{\text{star}}$) values. The lower plot shows a binned version of the data where the $y$-scale of planet mass has been divided by stellar mass. If planet mass and stellar mass were linearly related, then the solid line in the lower plot would be consistent with horizontal. However, it suggests a steeper relationship between host mass and planet mass. The dashed line is equivalent to $M_{\text{planet}} \sin i \propto M_{\text{star}}^{2.5}$. The error bars are from $\sqrt{\text{number}}$ statistics and are only indicative.

The relative lack of radial velocities even for the prominent M dwarfs arises because it is easier to obtain data for a given brightness rather than a particular radial velocity signal-to-noise ratio. Thus, few M dwarfs qualify for inclusion in magnitude-limited surveys. Despite this, some M dwarfs have made it into the large-scale radial velocity programmes carried out with the instrument–telescope combinations Lick [8], OHP [9], CORALIE-Swiss [10], HIRES-Keck [11], HARPS-ESO 3.6m [12] and the UCLES-AAT [13]. A few surveys have specifically targeted M dwarfs [14,15]. In addition to their relative small intrinsic brightness, M dwarfs are known to be typically rather active. Relative to more massive stars, their evolutionary time scales are rather drawn out [16], and thus their activity is long lived. Empirical observations from radial velocities have not, however, shown any additional jitter beyond that of other spectral types whose samples have been more carefully selected to avoid high activities [17].

Although relatively fewer M dwarf planets are known from radial velocities, the ones that are known are among the richest and most interesting exoplanets in terms of orbital spacings and dynamics [18]. One particularly interesting aspect of M dwarfs is that their relative faintness means that the location where liquid water might exist or the so-called habitable zone is rather close to the star (less than 0.1 AU). For a given mass exoplanet, the reflex velocity of a lighter host star is relatively larger, easier to detect and can be confirmed more quickly. Thus, despite the relatively few data points taken for them, exoplanets around M dwarfs rank high in the compilations of potentially habitable exoplanets, which are ranked in order of similarity to Earth (e.g. http://phl.upr.edu/projects/habitable-exoplanets-catalogue).

2. M dwarf planets

Although relatively few exoplanets have been discovered around M dwarfs, they have also been part of the ongoing development of the field of exoplanets. The first radial velocity discovery
of an M dwarf planet coming from GJ876 was by Delfosse et al. [19] and Marcy et al. [20], and they have also been discovered by transit (e.g. GJ1214b by [21]) and microlensing surveys (e.g. MOA-2007-BLG-192Lb by [22]).

The dependence of host mass on exoplanet location can be inferred from a plot similar to figure 1. The upper plot showing individual exoplanet detections indicates a relative lack of stars with masses below 0.7 $M_\odot$ around which planets have been found fairly uniformly in semi-major axes, unlike higher mass stars where there is a much greater prevalence beyond 1 AU and intermediate mass stars where there is a relative deficit from 0.1 to 1 AU. A number of features may be discerned, in particular that relatively few planets have been found around lower mass stars. It can also be seen that the distribution of M dwarf planets would seem to be relatively uniform in comparison with intermediate-mass stars (say around 1 $M_\odot$), which appear to have a pronounced lack of exoplanets between 0.1 and 1.0 AU and higher mass planets which appear to show few exoplanets with orbits less than 1 AU. It should be noted that there are a number of serious biases at play when considering a compendium of planets taken from surveys which have been operating with quite different instruments, data reduction and strategies. However, most of these findings run counter to the overall biases at play in detections; in particular, it is much easier to find signals with shorter semi-major axes. Thus, the relatively large number of short-period exoplanets around solar-type stars can be seen as a bias owing to these objects being efficiently detected to large volumes around solar-type stars in transit surveys but the relative deficit and the different mass distribution between, say, 0.3 and 3 AU should be robust to observational bias.

The wide range of stars and locations around which planets have been inferred to exist indicates that the planet formation process is very robust. The upper part of figure 2 shows a scatter plot of exoplanet masses and their host masses with the lower plot showing the median of planet mass divided by host mass. There are at least two interesting features: (i) there seem to be no exoplanets with masses below around 0.5 $M_{\text{Jup}}$ around stars with masses greater than 1.3 $M_\odot$ and (ii) while planet mass appears to broadly scale with mass for heavier host stars, for low-mass stars there is strong evidence that the median planet mass drops significantly towards lower masses. As with figure 1, there are many different biases at work, which potentially veil true underlying relationships. Notably, the mass cut-off is much more dramatic than the change in mass sensitivity, which scales with $\sqrt{\text{host mass}}$. It might be guessed that the lower mass exoplanets, at masses lower than 1.3 $M_\odot$, arise from transit objects; however, this is not the case and there are only a few M dwarfs that are known with transiting exoplanets and, as seen in figure 1, planets are found around M dwarfs at a range of semi-major axes. Inspection of the individual exoplanets below 0.5 $M_{\text{Jup}}$ indicates that they are drawn from a number of sources. Across the 0.7–1.3 $M_\odot$ region, there are indeed substantial numbers of transit-discovered sources and no transit sources at all around stars with masses greater than 1.6 $M_\odot$. Kennedy & Kenyon [23] anticipate that this is caused by the efficient dispersal of discs around massive stars preventing any disc migration. Based on radial velocity analysis of giant planets, Johnson et al. [24] find that the occurrence of planets increases linearly with stellar mass from around 3% at 0.5 $M_\odot$ to 14% by 2 $M_\odot$. Kepler results complete to much lower masses but only for short orbital periods indicate that the overall frequency is considerably higher but shows no spectral-type dependence [25]. It is also apparent that the multiplicity around a given planetary system appears to be somewhat sensitive to mass with few multiple planet systems appearing around high-mass stars. This might easily arise from the relative lack of data. However, the reduced median mass of M dwarf exoplanets would appear to arise owing to the relative lack of high-mass exoplanets in their orbit.

While it is clear from figure 2 that high-mass exoplanets do exist around M dwarfs, the existing radial velocity data have been used on average to pick out much lower mass objects than would be expected from a simple scaling of host mass and planet mass. It is possible that there has been something about the relatively few M dwarfs available at bright optical magnitudes folded with observational strategy that has led to a focus on a relatively few M dwarfs where reasonable signal-to-noise ratio could be obtained. In particular, the two major detection techniques of using a stabilized iodine cell or simultaneous ThAr lamp are reliant on optical flux for their detections.
It can be seen from figure 3 that there is little optical flux available and the radial velocity information is highly sensitive to the strength of features. Although transit searches have picked up a few M dwarfs, they are only sensitive to the close orbiting exoplanets. Nonetheless, it is much easier to find high-mass exoplanets, and thus the easiest explanation is that planet formation around M dwarfs produces proportionally much lower mass exoplanets.

3. Wavelength-dependent signals

The Template-Enhanced Radial velocity Re-analysis Application (TERRA) developed by Anglada-Escude & Butler [27] is a pipeline suite designed to improve the radial velocities achieved by the standard HARPS Data Reduction Software (DRS). Instead of cross-correlating with a binary mask (as done by the DRS), TERRA uses a high-resolution template (derived from a high signal-to-noise ratio version of the observed spectrum) to obtain a more optimal match to the observed spectrum. Measured against DRS, TERRA is most effective for M stars where stellar lines become more numerous and the template match offers significant improvements over the binary mask cross-correlation method. As demonstrated by Anglada-Escude & Butler [27], improvements of 15–27% in the RMS were achieved for M1.5–M6V stars.

TERRA has been used to improve the RMS of measurements for a number of interesting objects including the nearby M dwarfs GJ667C [18], enabling the presence of a planetary system to be inferred. Based on a reduction in GJ1061 data within the HARPS ESO archive, we find most of the signal is in the final nine reddest orders, covering the wavelength range of 6311–6878 Å (figure 4). The signal-to-noise ratio ranges from 16.5 to 25.9 with corresponding radial velocity uncertainties per order in the range of 5.4–11.7 m s$^{-1}$. Combining all orders yields 2.04 m s$^{-1}$. While GJ1061 provides a practical example of the difficulties of gaining sufficient signal-to-noise ratio on faint M dwarfs it is also notable that the time-series power offered by different wavelengths is somewhat different with redder regions presenting higher signal-to-noise ratios. For example, figure 5 shows a series of periodograms focused on successively redder wavelengths. It can be seen that the relative importance of different signals is dependent on the chosen wavelength region. Thus,
Figure 4. Extracted signal-to-noise (S/N) ratio and radial velocity (RV) uncertainty for each HARPS order for archival GJ1061 data reduced with TERRA. Most of the signal is in the reddest orders, with signal-to-noise ratio = 16.5 — 25.9 and radial velocity uncertainties of 5.4—11.7 m s$^{-1}$. The weighted, combined radial velocities from each order yield 2.04 m s$^{-1}$ precision. (Online version in colour.)

Figure 5. Periodogram of the residuals to the three-planet solution as a function of the blue cut-off. The top periodogram is obtained using the full spectrum radial velocities. The middle periodogram after losing the first 500 Å of blue coverage and the bottom periodogram obtained just using wavelengths redward of 5050 Å (aperture 40). The dashed line shows a false alarm probability of 1%. It can be seen that the periodogram signal strength is dependent on the red cut-off wavelength. (Adapted from [28].)
TERRA extends the concept of monitoring the strength of known activity features such as H\(\alpha\) and CaHK and shows a powerful new tool to validate signals; it can also distinguish other spectral regions that might give rise to activity signals.

4. Combining datasets

While planetary companions have been traditionally inferred from single instrument–telescope combinations, the confirmation of a signal with a different dataset is highly desirable. The online archives provided by most instrument–telescope combinations means that this is now practical for a number of nearby stars. Figure 6 gives an example of an object showing a probable signal in archival HARPS data which appears to be confirmed by recently acquired HARPS-TNG data. A few extra points obtained with a different telescope, instrument and data reduction system is potentially a robust method to confirm weak signals. In figure 7, we show the result of applying this methodology to UVES-VLT data on M dwarfs published by Zechmeister et al. [14] supplemented by data from the ESO-HARPS archive (http://archive.eso.org). In addition to verifying a number of known objects, this technique enables [29] the detection of a number of new objects shown as circled dots. It is notable that these occur at a range of periods, consistent with the previously known M dwarf planets (figure 1), and all have rather low mass as anticipated by the drop in masses found in the lower left of the panels in figure 2. The sensitivity analysis shown in figure 7 can be viewed as indicative for radial velocity-detected objects: for a given signal amplitude, detection probability increases substantially towards shorter periods and higher masses, nonetheless exhibiting significant non-uniformities owing to substantial differences in the data available for different objects.

5. The future: completing the census of M dwarfs

Most analyses of exoplanets around M dwarfs have been based on inferences from early to mid-type M dwarfs. At the moment, only a few of the very closest M5 and M6 objects have some precision radial velocity data taken for them and the relative lack of flux apparent in figure 3...
Figure 7. Planet detection probability in the combined UVES and HARPS dataset as functions of orbital period and minimum mass. The triangles represent the known planets orbiting all stars and those orbiting M dwarfs are outlined; planet candidates in our sample are shown as dots and those with high confidence are circled. The detection probabilities do not exceed 85% even at the high-mass short-period corner of the plot because there are six datasets where planetary signals could not be detected at all because of a combination of low number of measurements and evidence of a massive companion that prevented detections of additional companions owing to overparameterization of the benchmark model. (Online version in colour.)

means that even at these mid-M spectral types observations at longer wavelengths need to be performed in order to complete a meaningful census of mid-M dwarfs. Figure 8 shows velocity RMS values based on four data points taken over a week using UVES-VLT on M5 to M9 dwarfs. While four data points are inadequate for the detection of new planetary signals they do suffice to indicate that with suitable instrumentation and procedures it is possible to obtain m s\(^{-1}\) precisions at late spectral types. In particular, four objects in figure 8 can be seen to exhibit velocity RMS values significantly below 10 m s\(^{-1}\) and they have a range of spectral types between M5.5V and M9V. While it is not surprising that these objects with low velocity RMS also have low \(v\sin i\) (rotational velocity) values, and indeed there is a reasonable correlation between radial velocity RMS and \(v\sin i\), it is notable that radial velocity RMS appears to scale well with the relative strength of the H\(\alpha\) emission line. Although the H\(\alpha\) line does appear to vary significantly for any particular star, this variability might prove a useful indicator of orbital rotation and inclination. If a significant component of this variability arises from hot spots rotating in and out of view, then the range of observed activity will presumably be greater for edge-on than face-on orbits. So, it seems that radial velocity surveys of late-type M dwarfs will considerably benefit from the careful consideration for H\(\alpha\) in both selection and interpretation.

Even modest anticipated refinements in procedures and instruments mean that the discovery and characterization of exoplanets should continue to increase, as objects are found from a wide range of techniques. The power of characterization using several techniques has already been proved for the transiting M dwarfs, e.g. GJ436 [31]. As more M dwarfs are discovered and characterized with datasets from multiple techniques then a much deeper understanding of exoplanets around M dwarfs will be possible, allowing the impact of mass, metallicity and environment to be investigated. In the near term the continuing powerful combination of radial velocity together with other large-scale projects for transits (e.g. TESS), astrometry (e.g. GAIA)
Figure 8. Key stellar parameters plotted against radial velocity RMS. The plots are of $v\sin i$ versus radial velocity RMS (top), spectral type versus radial velocity RMS (middle) and activity ($\log_{10}(L_{H\alpha}/L_{bol})$) versus RMS velocity (bottom). The symbols used in all panels denote the signal-to-noise (S/N) ratios or S/N ratio intervals for each observed target: S/N ratio $< 15$ (squares), S/N ratio $< 30$ (circles), S/N ratio $< 60$ (triangles) and S/N ratio $> 100$ (diamonds). Similarly, photon noise-limited contours from Barnes et al. [26] are plotted in the top panel for S/N ratio $= 15, 30, 60$ and $120$, respectively (solid, long-dashed, short-dashed, dotted). Maximum and minimum values of luminosity are plotted as circles connected by a line for each star in the bottom panel. The arrowhead indicates that the lowest $H\alpha$ luminosity is a sensitivity limit, and equal to the equivalent width uncertainty. The stars with the highest $v\sin i$ values are most discrepant from the photon noise-limited case, indicating the importance of activity as an indicator of expected precision. (Adapted from [30].) (Online version in colour.)

and interferometry (e.g. Magellan Ridge) and deep imaging (e.g. JWST) should also provide important new insights.

Acknowledgements. We acknowledge the unstinting efforts of the archivists everywhere, in particular archive.eso.org, exoplanets.org and exoplanets.eu. These results were based on observations made with ESO Telescopes at the La Silla Paranal Observatory, Chile, and Telescope National Gallileo, Spain.
References


