Radial velocity studies of low-mass stars

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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 emphasise (1) the wavelength sensitivity of radial velocity signals, (2) the combination of radial velocity data from different experiments for robust detection of small amplitude signals and (3) the selection of targets and radial velocity interpretation of late-type M dwarfs should consider Hα behaviour.

Key words: M dwarfs; Radial velocities; Exoplanets.

1. Introduction

Over the last 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 (e.g., Wittenmyer et al. 2011). 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 γ Cep Bb by Campbell & Walker (1988) and has been driven by a usually healthy competition between different research groups and techniques.

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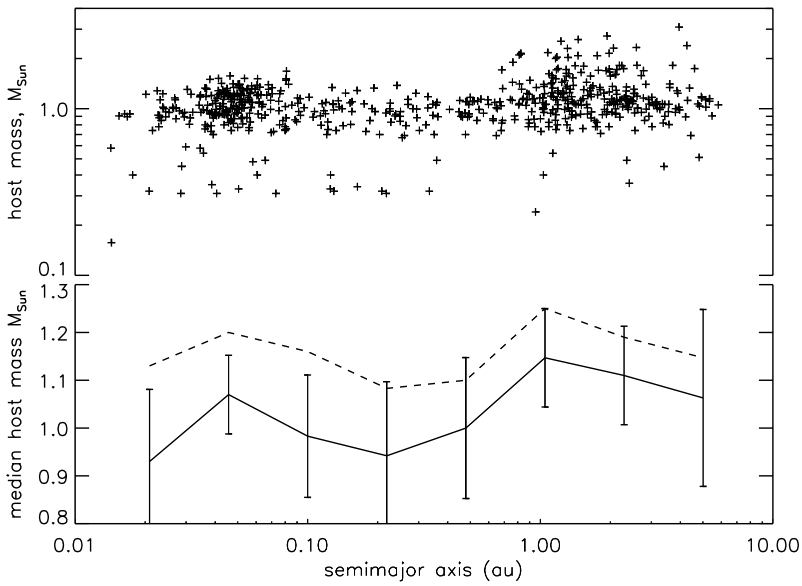

Figure 1. The plot shows median $M_{star_\odot}$ values for exoplanet host stars against semimajor axis of their exoplanets (based on all exoplanets with radial velocity from exoplanets.org - approximately 70% of these were found first from radial velocity data). The upper plot shows all published exoplanets included in exoplanets.org orbits database as inferred from radial velocities: the lower plot is a binned version which indicates median $M_{star_\odot}$ values; the dashed line represents the sub sample of all hosts with a planet that has a minimum mass above 1 M_{JUP} sin i. The error bars are from $\sqrt{(number)}$ statistics and are only indicative.

Although exoplanets have been discovered around a very wide range of objects (e.g., Wolzcan & Frail 1992) 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 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 Fig. 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 toward 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 to 0.5 M_{Sun}. Despite being the most abundant stars in our neighbourhood, relatively few exoplanets have been found and only

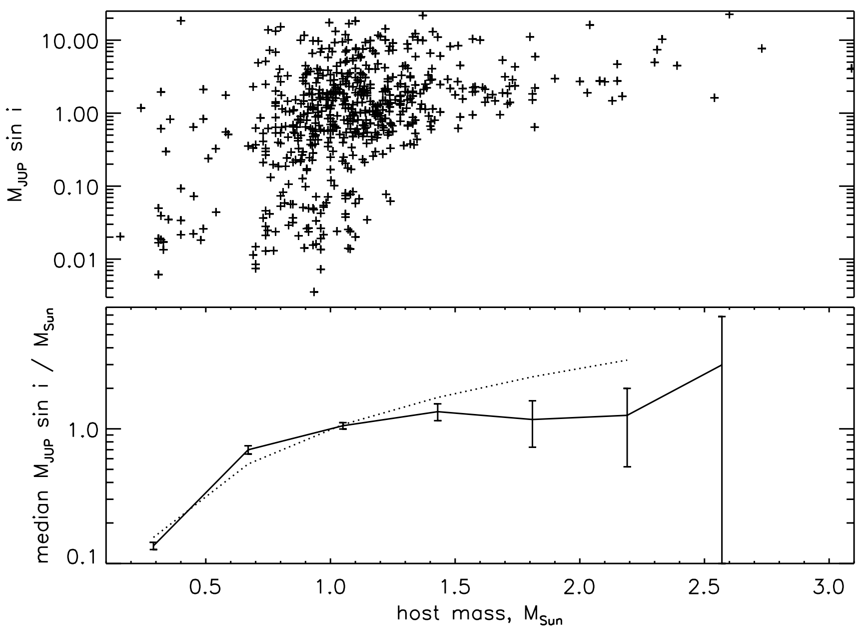

Figure 2. For known planet hosting stars selected as per Fig. 1, the upper plot shows planet mass ($M_{\rm JUP}$) versus stellar mass ($M_{{\rm star}_\odot}$) values. The lower plot shows a binned version of the data where the y scale of planet mass has been divided by stellar mass. If planet mass and stellar mass were linearly related then the solid line in the lower plot would possess a gradient of zero. However, it suggests a steeper relationship between host mass and planet mass. The dashed line is equivalent to $\rm M_{planet}$ sin $i \propto \rm M_{star}^{2.5}$. The error bars are from $\sqrt{(number)}$ statistics and are only indicative.

around the hottest M dwarfs. In this work we will 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. Nearby bright 'Solar-like' stars such as α Cen (e.g., Dumusque et al. 2012) and τ Ceti (e.g., Tuomi et al. 2013a) 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 Fig. 2 (exoplanets.org curated by Wright et al. 2011 and exoplanet.eu curated by Schneider et al. 2011)

The relative lack of radial velocities for even for the prominent M dwarfs arises because it is easier to obtain data to a given brightness rather than a particular radial velocity signal-to-noise. 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 (e.g., Fischer, Marcy & Spronck 2013), OHP (e.g., Bouchy et al. 2009), CORALIE-Swiss (e.g., Queloz et al. 2000), HIRES-Keck (e.g., Vogt et al. 2000), HARPS-ESO3.6m (e.g., Pepe et al. 2000) and the UCLES-AAT (e.g., Jones et al. 2002). A few surveys have specifically targeted M dwarfs (e.g., Zechmeister et al. 2009 and Bonfils et al. 2013). In addition to their relative small intrinsic brightness M dwarfs are known to be typically rather active. Relative to more massive stars their evolutionary timescales are rather drawn out (e.g., Laughlin, Bodenheimer & Adams 1997) 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 (e.g., Wright 2005).

Although relative 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 (e.g., Anglada-Esude et al. 2013, Mayor et al. 2009). 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 (<0.1au). 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-catalog).

2. M dwarf planets

Although relatively few exoplanets have been discovered around M dwarfs, they have been part of the ongoing development of the field of exoplanets. The first radial velocity discovery of an M dwarf planet coming from GJ876 by Delfosse et al. (1998) & Marcy (1998) and they have been discovered by transit (e.g., GJ1214b by Charbonneau et al. 2009) and microlensing surveys (e.g., MOA-2007-BLG-192Lb by Bennett et al. 2008).

The dependence of host mass on exoplanet location can be inferred from a plot such as Fig. 1. The upper plot showing individual exoplanet detections indicates a relative lack of stars with masses below 0.7 $M_\odot$ around which planets around lower mass stars 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 maybe discerned, in particular, remembering their relative abundance notably few planets have been found around lower mass stars. It can also been seen that the distribution of M dwarf planets would seem to be relatively uniform in comparison to intermediate mass stars (say around 1 M_{Sun}) 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. It is clear that the overall mass function peaks toward lower masses (e.g., Butler et al. 2009, Lopez & Jenkins 2012). Thus, 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 due 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 Fig. 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: (1) there seem to be no exoplanets with masses below around 0.5 $M_{\rm Jup}$ around stars with masses greater than 1.3 $M_{\rm Sun}$, (2) 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 Fig. 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 $\sqrt{\rm hostmass}$. It might be guessed that the lower mass exoplanets, at masses lower than 1.3 $M_{\rm Sun}$, 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 Fig. 1 planets are found around M dwarfs at a range of semi-major axes. Inspection of the individual exoplanets below 0.5 $M_{\rm Jup}$ indicates that they are drawn from a number of sources. Across the 0.7-1.3 $M_{\rm Sun}$ region there are indeed substantial numbers of transit-discovered sources and no transit sources at all around stars with masses greater than 1.6 $M_{\rm Sun}$. Kennedy & Kenyon (2009) anticipate that this is caused by the efficient dispersal of disks around massive stars preventing any disk migration. Based on radial velocity analysis of giant planets Johnson et al. (2010) find that the occurrence of planets increases linearly with stellar mass from around 3% at 0.5 $M_{\rm Sun}$ to 14% by 2 $M_{\rm Sun}$. 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 (Fressin et al. 2013). 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 due to the relative lack of high mass exoplanets in their orbit.

While it is clear from Fig. 2 that high mass exoplanets do exist around M dwarfs, the existing radial velocity data has 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. Relatively few M dwarfs are available at bright optical magnitudes and the observational strategy has typically focused on the relatively few M dwarfs where reasonable signal-to-noise could be obtained. In particular, the two major detection techniques of using a stabilised Iodine cell or simultaneous ThAr lamp are reliant on optical flux for their detections. It can be seen from Fig. 3 that there is little optical flux available and the radial velocity information is highly

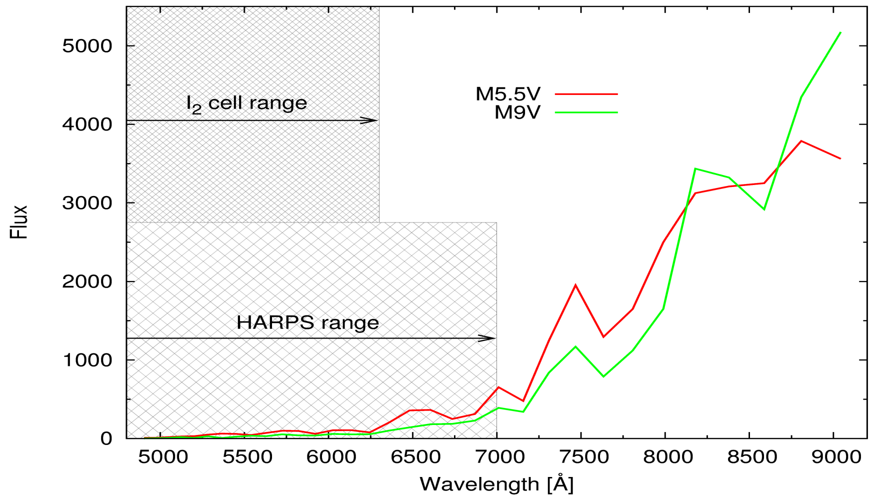

Figure 3. The mean flux level of the 33 extracted MIKE-Magellan orders covering 4830 - 9172Å for M5.5V and M9V targets (scaled to the same level at I band centre). Also shown are the optical I2 cell regime and the ThAr coverage that overlap with the MIKE red arm data. We find that 92% (M5.5V) and 95% (M9V) of the flux in the MIKE-Magellan 4830 - 9172Å region is located at 7000 - 9200Å . It should be noted that the is represents the observed sensitivity (i.e., instrument and detector) and is not a flux calibrated spectrum (adapted from Barnes et al. 2012).

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 2012) 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 S/N 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 signifcant improvements over the binary mask cross-correlation method. As demonstrated by Anglada-Escude & Butler (2012), 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 GJ 667 C (Anglada-Escude et al. 2013), enabling the presence of a planetary system to be inferred. Based

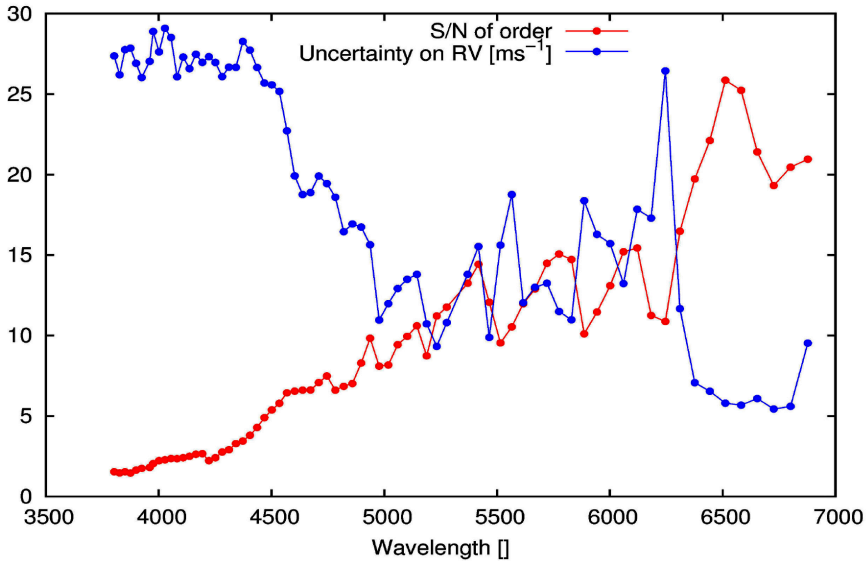

Figure 4. Extracted signal-to-noise ratio and radial velocity uncertainty for each HARPS order for archival GJ 1061 data reduced with TERRA. Most of the signal is in the reddest orders, with S/N = 16.5 - 25.9 and radial velocity uncertainties of 5.4 - 11.7 m/s. The weighted, combined radial velocities from each order yield 2.04 m/s precision.

on a reduction of GJ 1061 data within the HARPS ESO archive, we find most of the signal is in the final 9 reddest orders, covering the wavelength range 6311 - 6878 (Fig. 4). The S/N ranges from 16.5 - 25.9 with corresponding radial velocity uncertainties per order in the range 5.4 - 11.7 m/s. Combining all orders yields 2.04 m/s. While GJ1061 provides a practical example of the difficulties of gaining sufficient S/N 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. For example, Fig. 5 shows a series of periodograms focussed on successively redder wavelengths. It can be seen that the relative importance of different signals is dependent on the chosen wavelength region. Thus TERRA extends the concept of monitoring the strength of known activity features such as Hα and CaHK and shows a powerful new tool to validate signals and can 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 this is now practical for a number of nearby stars. Fig. 6 gives an example of an object showing a probable signal in archival HARPS

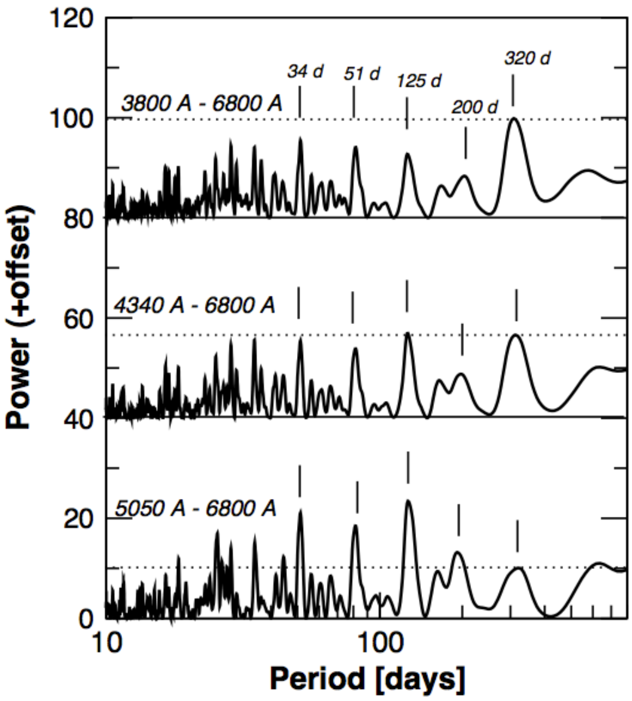

Figure 5. Periodogram of the residuals to the three planet solution as a function of the blue cutoff. The top periodogram is obtained using the full spectrum radial velocities. The middle periodogram after loosing the first 500Å of blue coverage and the bottom periodogram obtained just using wavelengths red ward of 5050Å (aperture 40). The dashed line shows a false alarm probability of 1%. It can be seen that periodogram signals strength is dependent on the red cutoff wavelength (adapted from Tuomi et al. 2013b).

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 Fig. 7, we show the result of applying this methodology to UVES-VLT data on M dwarfs published by Zechmeister et al. (2009) supplemented by data from the ESO-HARPS archive (http://archive.eso.org). In addition to verifying a number of known objects, this technique enables detection of a number of new objects shown as circled red dots (Tuomi et al. 2014, submitted). It is notable that these occur at a range of periods, consistent with the previously known M dwarf planets (Fig. 1) and all have rather low mass as anticipated by the drop in masses found in the lower left of the panels in Fig.2. The sensitivity analysis shown in Fig. 7 can be viewed as indicative for radial velocity detected objects: for a given signal amplitude, detection probability increases substantially toward shorter periods and higher masses nonetheless exhibiting significant non-uniformities due to substantial differences in the data available for different objects.

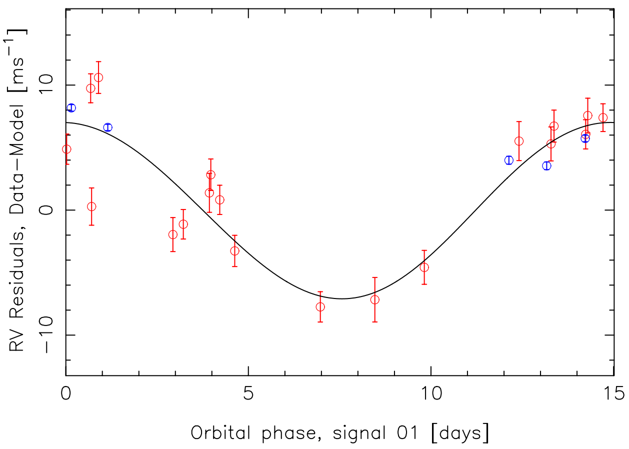

Figure 6. The red points are acquired with HARPS-N and the blue points with HARPS-S.

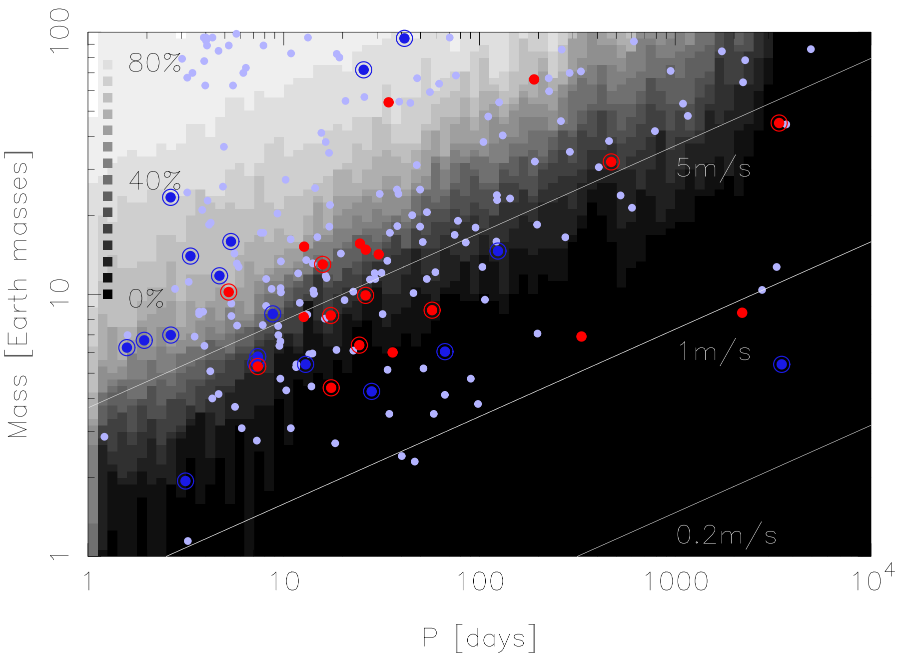

Figure 7. Planet detection probability in the combined UVES and HARPS data set as functions of orbital period and minimum mass. The various dots represent the known planets orbiting all stars (light blue dots), known planets orbiting M dwarfs (circled blue dots), and planet candidates in our sample (circled red dots). The detection probabilities do not exceed 85% even at the high-mass short-period corner of the plot because there are six data sets where planetary signals could not be detected at all due a combination of low number of measurements and evidence of a massive companion that prevented detections of additional companions due to overparameterisation of the benchmark model (version of Tuomi et al. 2013, submitted).

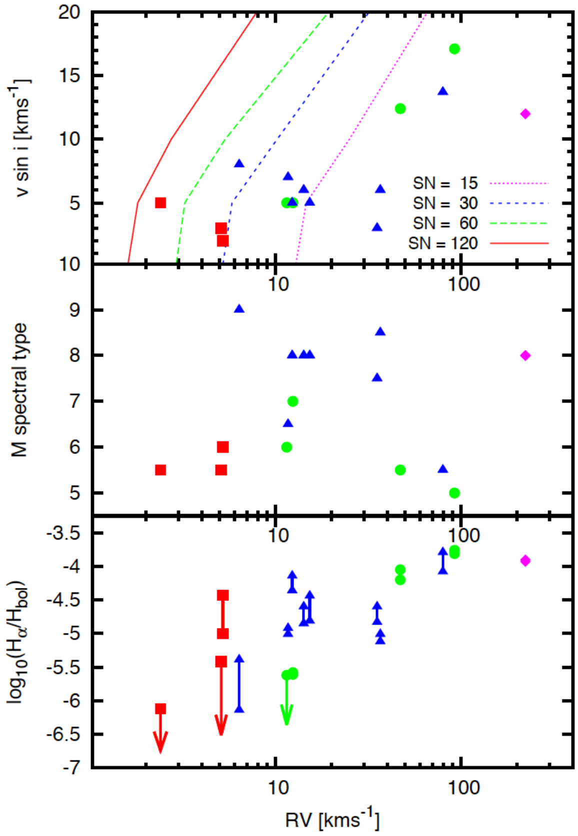

Figure 8. Key stellar parameters plotted against radial velocity RMS. The plots are of v sin$i$ vs radial velocity RMS (top), spectral type vs radial velocity RMS (middle) and activity (log10($L_{H\alpha}$/ L_{bol})) vs RMS velocity (bottom). The symbols and colours used in all panels denote the S/N ratios or S/N ratio intervals for each observed target: S/N $<$ 15 (red squares), S/N $<$ 30 (green circles), S/N $<$ 60 (blue triangles), S/N $>$ 100 (magenta diamonds). Similarly, photon noise limited contours from Barnes et al. (2012) are plotted in the top panel for S/N = 15, 30, 60 and 120 respectively (red/solid, green/long-dash, blue/short-dash, magenta/dotted). Maximum and minimum values of luminosity are plotted as circles connected by a line for each star in the bottom panel. The arrow head indicates that the lowest Hα 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 Barnes et al. 2014).

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 Fig. 3 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. Fig. 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 precisions at late spectral types. In particular four objects in Fig. 8 can be seen to exhibit velocity RMS values significantly below 10 m/s 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 $v \sin i$, the more striking relationship is that radial velocity RMS appears to scale well with the relative strength of the Hα emission line. Although the Hα 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 careful consideration for Hα both in selection and interpretation. Nonetheless it should be appreciated that late M dwarfs are on the whole rapid rotators (e.g., Jenkins et al. 2009) and that the implied rotation-activity relationship in Fig. 8 means that their radial velocity data is likely to be plagued by stellar activity.

Even modest anticipated refinements in procedures and instruments mean that the discovery and characterisation of exoplanets should continue to increase as objects are found from a wide range of techniques. The power of characterisation using several techniques has already been proven for the transiting M dwarfs, e.g., GJ436 (von Braun et al. 2012). As more M dwarfs are discovered and characterised 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) and interferometry (e.g. Magellan Ridge) and deep imaging (e.g., JWST) should also provide important new insights.

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