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The Hobby-Eberly Telescope M-Dwarf Planet Search Program:

New Observations and Results

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The Hobby-Eberly Telescope M-Dwarf Planet Search Program: New Observations and Results

by

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For my wife, Emily Christina Bartlett.

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The Hobby-Eberly Telescope M-Dwarf Planet Search Program: New Observations and Results

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The University of Texas at Austin, 2010

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As part of the McDonald Observatory M dwarf planet search program, we present the results and detection limits for our high-precision radial velocity survey of 99 M dwarf stars. We also detail our efforts to improve the precision of our RV measurements as well as our frequency analysis methods. For any RV program, it is essential to obtain as high a precision as possible; increasing sensitivity can realistically reveal terrestrial-mass planets with our data. M dwarfs provide a unique opportunity to study these lower-mass planets (the so-called "super-Earths") from ground-based facilities; such planets are mostly undetectable around FGK stars, whose larger masses result in much smaller RV amplitudes. However, the low intrinsic luminosities of the M spectral type make it difficult to obtain high S/N measurements for a statistically significant sample, making our analysis improvements especially critical. Finally, we conduct a statistical analysis of the 21 known M dwarf planets[1]. In particular, we use the photometric metallicity calibration for M dwarfs described in Johnson and Apps (2009) to further explore the frequency of planetary systems as a function of stellar metallicity. Our analysis confirms the correlation between stellar mass and the presence of giant planets, but also reveals a significant metallicity dependence on the presence of high-mass planets for M dwarfs. We show that the metallicities of our target sample are evenly distributed around solar [M/H], eliminating the possibility that the results of our survey will be biased due to metallicity effects. The frequency and characteristics of planets around M stars provides important insight into planet formation theories, especially for giant planets, which appear to form less easily around low-mass primaries. While previous results suggesting a dearth of short-period Jovian planets around M stars still holds, there is now a long enough observational time baseline to begin to characterize the frequency of planets with lower masses and larger orbital separations around these stars as opposed to other main sequence stars.

[1]This research has made use of the Extrasolar Planets Encyclopaedia (http://exoplanet.eu).

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Chapter 1

Introduction

In recent years, the field of exoplanet studies has moved from simply identifying planets to characterizing their compositions, dynamics, and formation mechanisms. However, while there are now more than 430 known exoplanet systems, the large majority of those orbit solar type stars. There are a number of reasons for this bias; FGK stars are abundant and relatively bright, ideal for statistically significant observational surveys, and there is obvious interest in sunlike stars for astrobiological purposes. Moreover, it is likely that there are real physical factors that make planet discoveries more likely around intermediate-mass stars. Johnson et al. (2007) explore planet fraction as a function of stellar mass, concluding that the observed planet population peaks for A stars, and drops off for the low-mass end of the main sequence. Nevertheless, there is much to be gained from the study of M-dwarf planets. From a practical standpoint, considering that the radial velocity (RV) amplitude K imparted on a star from an orbiting planet is given by

$$K = \sqrt{\frac{G}{1-e^2}}\frac{m\sin i}{\sqrt{(M_*+m)a}}$$

it can be shown that in most cases, M dwarfs provide the best opportunity to observe super-Earth planets (planets with $M \sin i \leq 10 M_{\oplus}$) with the RV technique (e.g. Correia et al. 2010, Mayor et al. 2009, and Forveille et al. 2009). Data for this mass regime is currently limited for all stellar types, and it remains unknown whether the accepted hypotheses regarding population statistics and formation mechanisms for the well-sampled Jovian planets hold for super-Earths.

In addition, although previous results from our M-dwarf survey confirm that close-in Jovian planets are much rarer around M stars than their FGK counterparts, observational time baselines for M dwarfs are only now growing long enough to be sensitive to large planets at wider orbital radii. The initial conclusions drawn from the rarity of hot Jupiters for M dwarfs (Endl et al. 2006) suggest that the properties of these stars–shallow gravitational wells, long dynamical timescales, etc–inhibit the formation of gas giant planets, but recent results (Johnson et al. 2007, Butler et al. 2006, for example) reveal the presence of an increasing population of Jovian planets around M stars. These planets will probably not disprove the notion that Jupiters are rarer for lower-mass stars, but such conclusions merit re-evaluation in light of these discoveries. The possibility exists, for example, that the shortage of observed Jovian planets in M dwarf systems is due to a lack of gravitational migration rather than an actual population deficit.

With the addition of the planet in the GJ 179 system (Howard et al. 2010), discovered in conjunction with McDonald Observatory, and excluding planets discovered via gravitational microlensing, for which there remains large uncertainty as to the spectral types of the host stars, there are now 21 planets known to reside in 16 M dwarf systems. Using this sample, we perform a preliminary statistical analysis of these planets. Such statistics are vital to understanding the general population of planets in the Galaxy, as more than 70 percent of stars in the Milky Way are M-type (Henry et al. 1999). This bears important implications for astrobiology; Lunine (2009) points out that M dwarf planets may be the most common habitable environments in the Galaxy, and suggests an extended robotic mission to Titan to study the type of small, cold bodies believed to be most common around low-mass stars. Tarter et al. (2007) conclude that despite the smaller habitable zones for M stars, the planets that form there could be habitable, with stable atmospheres and oceans. Scalo et al. (2007) point out that if a planet can remain habitable beyond the first Gyr of an M dwarf's lifetime, when stellar activity would likely threaten biological activity, it can potentially provide a stable habitable environment over timescales far exceeding the Hubble time.

This paper, the fourth installment from the McDonald Observatory M-Dwarf Survey, presents updated results from 8 years of surveying 99 M-dwarf stars for RV planet signatures. We include a discussion of our updated data reduction procedures, and provide statistics for our sample, as well as for the 16 known M-dwarf planet systems. Our analysis reveals a significant stellar metallicity dependence on the masses of observable M dwarf planets.

Chapter 2

Description of the Data

Our data set consists of observations from McDonald Observatory's HRS Spectrograph (Tull 1998) on the Hobby-Eberly Telescope, with supplementary data from the Tull Coude Spectrograph on the 2.7m telescope. The spectra are taken at a resolution R=60,000, and the wavelength calibration is acquired simultaneously via the use of a molecular iodine (I_2) absorption cell in the light path. The data set and observation method are described in greater detail in Endl et al. (2003).

RVs are extracted by modeling the observed data with a template stellar spectrum and a reference I_2 absorption spectrum to simultaneously calibrate the wavelength scale and remove effects introduced by the instrument (see Valenti et al. 1995 and Butler et al. 1996 for details on the modeling procedure, and Endl et al. 2000 for our implementation of the method). Due to the lower flux levels of most M dwarfs, the typical RV scatter due to photon noise is greater than for other main sequence stars, resulting in a typical precision of $\sim$6 m/s for our sample.

Chapter 3

RV Analysis: The Generalized Lomb-Scargle Periodogram

In analyzing time-series RV data for periodic signals, planet searches have long relied on the Lomb-Scargle (L-S) periodogram defined in Lomb (1976) and Scargle (1982) because of its ability to treat data that are unevenly spaced in time. While this technique was ideal for RV surveys (Horne and Baliunas 1986), which include years' worth of sporadically acquired data, it sacrificed the ability to consider error bars on individual measurements. Furthermore, it required the data to be normalized to zero mean, removing the ability to evaluate a floating-mean solution.

The generalized Lomb-Scargle periodogram, developed by Zechmeister and Kürster (2009) solves both of these problems by fitting sine curves of the form $y = a\cos\omega t + b\sin\omega t + c$ to the data using χ^2 minimization. The generalized power spectrum is given by

$$P(\omega) = \frac{1}{2\sigma_y^2}\frac{(\sum w_i y_i \cos\omega\bar{t_i} - \sum w_i y_i \sum w_i \cos\omega\bar{t_i}/\sum w_i)^2}{\sum w_i \cos^2\omega\bar{t_i} - (\sum w_i \cos\omega\bar{t_i})^2/\sum w_i} + \frac{1}{2\sigma_y^2}\frac{(\sum w_i y_i \sin\omega\bar{t_i} - \sum w_i y_i \sum w_i \sin\omega\bar{t_i}/\sum w_i)^2}{\sum w_i \sin^2\omega\bar{t_i} - (\sum w_i \sin\omega\bar{t_i})^2/\sum w_i},$$

where $w_i = \frac{1}{\sigma_{y,i}^2}$, $\quad \bar{t_i} = t_i - \tau_\omega$, $\quad$ and

$$\tan 2\omega\tau_\omega = \frac{\sum w_i \sin 2\omega t_i - 2\sum w_i \sin \omega t_i \sum w_i \cos \omega t_i / \sum w_i}{\sum w_i \cos 2\omega t_i - [(\sum w_i \cos \omega t_i)^2 - (\sum w_i \sin \omega t_i)^2] / \sum w_i} \ .$$

To estimate the significance of a given peak in the periodogram, we calculate the false alarm probability (FAP). Our FAPs are calculated using Equation 24 of Zechmeister and Kürster (2009), where we take M, the number of independent frequencies evaluated, to be

$$M = \frac{\Delta f}{\delta f}, \qquad \Delta f = \frac{1}{T_{min}} - \frac{1}{\tau}$$

with T_{min} being the minimum period considered, τ the time baseline of our observations, and δf the resolution of our frequency-space calculation.

We attempt to quantify the improvement in performance given by the use of the generalized L-S periodogram instead of the original. Figure 3.1 shows the power spectrum for our RV data on GJ 436 as calculated with the traditional L-S periodogram and with the generalized method. The peak for the 2.64-day planet is roughly 20 percent higher when evaluated with the generalized equation. To simulate the effect of the power increase on the number of observations required to identify a planet, we calculated a series of periodograms for GJ 436, progressively including more data points with each, and determining how quickly the 2.64 day peak crossed the power threshold for a false-alarm probability (FAP) of 0.01. In the case of GJ 436, the detection occurred after 47 data points for the generalized L-S method, and after 55 points with the original L-S periodogram, or an improvement of 22 percent. The 47th and 55th RV points were temporally separated by 86 days, corresponding to a confirmed detection 20 percent sooner.

The dramatic improvement given by the generalized L-S power spectrum can be attributed to our HET HRS data. Our RV points tend to have a wide range of uncertainties for reasons mentioned in Chapter 2. Because certain data points have considerably larger error bars than others, it is essential to consider individual weights when computing the periodogram. It can be shown that for data sets with equally weighted points, the above equations reduce to the unweighted L-S power spectrum. Therefore, for data with more uniform error bars, or sets where more uncertain points have been removed, the increase in power resulting from the use of the generalized L-S periodogram will be negligible.

It is therefore vital to use the generalized L-S technique when combining data sets from multiple instruments, where some points may have drastically larger error bars than others. Figure 3.2 gives the original and generalized L-S periodograms for GJ 581. The plots are calculated using our own data, as well as data from HARPS at La Silla published in Mayor et al (2009). The generalized power spectrum displays the peaks of the known planets in the GJ 581 system, while the classic periodogram fails to produce the correct peaks.

Table 3.1 lists the peak of the generalized L-S power spectrum for every star in our sample for which we have adequate data, and indicates the power for which the FAP drops below 0.01. We ignore peaks at periods below 2 days

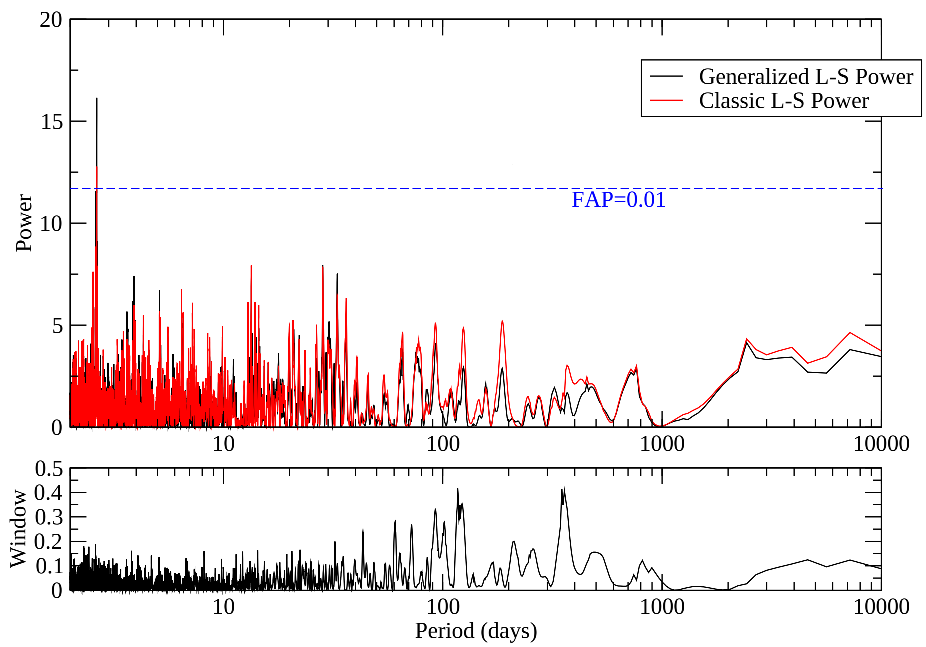

Figure 3.1: The Lomb-Scargle periodogram and window response function for GJ 436, as calculated with the original method (red) and the generalized equation (black). The blue dotted line represents the power above which the false-alarm probability drops below 0.01.

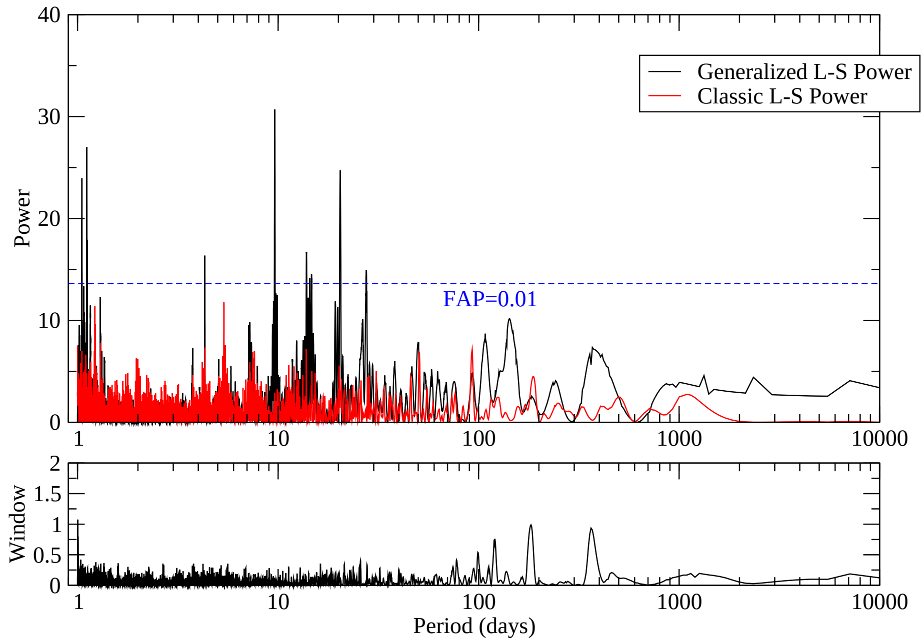

Figure 3.2: The Lomb-Scargle periodogram and window response function for GJ 581, as calculated with the original method (red) and the generalized equation (black) using our data combined with data published in Mayor et al (2009). The blue dotted line represents the power above which the false-alarm probability drops below 0.01.

because of the severe aliasing problems arising at periods around 1 day. Cases where a peak exceeds the FAP=0.01 threshold due to a peak in the accompanying window function, or corresponds to a period outside our observational time baseline, are marked with an asterisk to indicate a "false positive."

Table 3.1: The results of the generalized Lomb-Scargle periodogram for our targets. Peaks marked with an asterisk exceed the FAP=0.01 threshold because of a peak in the window function, and should not be considered real detections.

Star	Number of RV Points	Period of Peak (days)	Maximum Power	FAP
GJ 1051	8	64.65	4.68*	3.48
GJ 109	11	2.84	5.36*	4.87
GJ 1170	13	15.39	4.51	5.66
GJ 134	19	945.6	5.56	7.52
GJ 155.1	14	39.43	7.11*	6.05
GJ 162	13	272.9	5.12	5.67
GJ 176	68	10.23	7.28	12.13
GJ 179	17	5.08	7.04*	6.99
GJ 181	16	4.31	6.28	6.71
GJ 184	21	7027	9.33*	8.04
GJ192	17	7120	8.44*	7.02
GJ 2128	15	40.02	6.08	6.40
GJ 213	12	363.8	6.23*	5.27
GJ 251.1	25	3.94	5.88	8.80
GJ 270	32	7131	25.15*	9.88
GJ 272	44	3.24	7.96	11.01

Table 3.1 cont'd.				
Star	Number of RV Points	Period of Peak (days)	Maximum Power	FAP
GJ 277.1	30	2.84	5.83	9.62
GJ 281	23	3.10	8.42	8.47
GJ 289	20	6.52	5.87	7.82
GJ 308.1	49	24.99	10.27	11.34
GJ 328	27	5562	17.97*	9.19
GJ 353	25	3.78	5.43	8.86
GJ 378	11	91.35	7.39*	4.87
GJ 3801	10	3.24	5.03*	4.39
GJ 38	14	2.76	5.00	5.95
GJ 4092	11	3.88	4.33	4.86
GJ 411	51	3.86	12.37*	11.54
GJ 430.1	32	361.2	10.99*	9.70
GJ 436	66	2.64	16.15	12.15
GJ 447	11	8.78	4.62	4.81
GJ 476	8	16.07	3.80*	3.47
GJ 480	9	13.87	4.71*	3.97
GJ486	11	55.51	4.09	4.86
GJ 535	27	9.79	7.74	9.19
GJ 552	25	2.60	6.87	8.85
GJ 563.1	33	2.17	6.71	10.03

Table 3.1 cont'd.				
Star	Number of RV Points	Period of Peak (days)	Maximum Power	FAP
GJ 581	37	5.37	11.55	10.42
GJ 655	57	7.99	6.02	11.68
GJ 671	20	60.40	6.62	7.79
GJ 687	14	15.09	5.54	6.05
GJ 70	7	2.00	3.62*	3.00
GJ 730	39	3.18	6.32	10.49
GJ 731	17	3.74	6.44	7.02
GJ 813	14	1294	5.51	5.89
GJ 839	22	6.11	6.85	8.25
GJ 846	11	18.86	4.55	4.86
GJ 849	12	38.74	5.69*	5.29
GJ 864	35	6813	30.14*	10.16
GJ 87	28	2.00	6.29	9.35
GJ 895	14	5.12	4.51	6.04
GJ 899	14	5.50	5.75	6.01
GJ 9381	16	2.49	4.93	6.68
GJ 96	20	2.43	10.23*	7.79

Chapter 4

Statistics

Various mechanisms have been proposed to explain the low frequency of detected planets around M dwarfs as opposed to higher-mass stars. Laughlin et al. (2004) show that the longer dynamical timescales for M dwarf protoplanetary disks, combined with the likelihood that the disks will be evaporated by radiation pressure due to the shallow gravitational well of the stars, should severely inhibit the formation of Jovian planets via core accretion. Furthering the difficulty of building giant planets through core accretion, it is generally agreed that the amount of mass initially present in a protoplanetary disk will decrease proportionally to the stellar mass, although Raymond et al. (2007) point out that the exact form of this dependence is unknown. Ida and Lin (2005b) simulate core accretion models where the disk surface densities of gas and dust vary proportionally to $(M_*/M_\odot)^2$, concluding that the lack of observed gas giants in M dwarf systems is consistent with the predicted planet population for low-mass stars.

Of course, if core accretion is not the only mechanism for planet formation, then an alternate explanation may exist. Boss (2006) shows that the problem of disk evaporation can be circumvented if Jovian planets form through gravitational instability of the protoplanetary disk. In this model, gas giants can form around M stars in times on the order of 10^3 years, well within the lifetime of the disk. If gravitational instability is in fact forming giant planets in M dwarf systems, we must conclude that migration is not as effective in this scenario, resulting in the gas giants remaining in orbital separations that are not yet within the detection limits of our survey. Boss (2006) does caution that Neptune- and lower-mass planets are unlikely to have formed through disk instability, so the statistics on those planets will still be affected by the limitations of the core accretion model for M dwarfs.

It is also well established that planet fraction will vary as a function of the parent star's metallicity (Fischer and Valenti 2005). Ida and Lin (2004) attribute the trend to an increasing dust fraction in protoplanetary disks for more metal-rich stars, allowing for faster planetary core formation. This may be an additional strike against the likelihood of detecting planets in M-dwarf systems; several observations (Bonfils et al. 2005 and Casagrande et al. 2008, among others) indicate that M stars are metal deficient compared to other main sequence stars in the solar neighborhood, although Johnson and Apps (2009) refute those results. The combination of factors detrimental to planet formation for low-mass stars seems to indicate that while continued observations will certainly reveal more M dwarf planets, the observed scarcity of planets in the low stellar mass regime is likely a real effect, and higher mass stars will always show higher planet populations.

4.1 Stellar Mass

In an attempt to estimate the relative importance of individual properties of the parent star on the presence of planets, we derive stellar masses and metallicities for our sample, and for the rest of the 16 M dwarfs with published planets. Stellar masses were calculated using the Delfosse et al. (2000) K-band mass-luminosity relation, which is particularly useful for separating the effects of stellar mass and metallicity since it is shown to be independent of stellar metallicity. The five stars in our sample whose absolute K-band magnitudes are outside the range where the relation is valid were omitted from our stellar mass analysis. Photometric data were taken from the 2MASS survey[2], the Hipparcos catalog (Turon et al. 1993), and the TASS Mark IV survey (Richmond 2007), with the exceptions of GJ 581 and GJ 1214, for which we use the photometry and parallax information given in Bonfils et al. (2005) and Charbonneau et al. (2010), respectively.

Figure 4.1 shows the distribution of our sample in terms of stellar mass, as well as the distributions of all M dwarfs with confirmed Jovian planets, and those with planetary systems that do not include a gas giant. We define a Jovian planet as a planet with $M \sin i \geq 0.3 M_{Jup}$. Evidently, the high-stellar-mass end of our sample covers the transition between early M- and late K-type stars. As with any M dwarf survey, our apparent magnitude limited sample is biased toward the brighter and therefore more massive early M and late

[2] This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France

K stars. The stars in our target list have an average mass of 0.53±0.1 $M_{\odot}$, compared to 0.53±0.2 $M_{\odot}$ for the M dwarfs with known Jovian planets and 0.38±0.1 $M_{\odot}$ for those with only sub-Jupiter planets.

To evaluate the relationship between our data set and the sample of M dwarfs with known planets, we perform a Kolmogorov-Smirnov (K-S) test to determine the likelihood that the sets are drawn from the same distribution. Our K-S test indicates a 90 percent probability that our sample and the M stars hosting Jovian planets are drawn from the same distribution. Conversely, it gives only a 4 percent probability that our sample is drawn from the same distribution as the set of M dwarf planetary systems without gas giants. As a consistency check, the set of stars with Jupiter-mass planets and the set of all M dwarf planet hosts, which obviously come from the same distribution, produce a result of 96 percent with the K-S test. Similarly, the set of sub-Jupiter systems matches the set of all planets at the 87 percent level. Given the bias of our sample towards brighter, more massive stars, and considering the strong correlation between our targets and the M stars with published gas giant planets, the K-S test appears to confirm that the mass of the parent star will likely determine whether its planetary system contains a Jovian planet.

Delfosse et al. (2006) performed a preliminary analysis of planetary mass as a function of stellar mass for M dwarfs. Their sample included the first six published M dwarf planets, and primarily compared the masses of those planets to the masses of all other known planets, concluding that M stars as a whole tend to host smaller planets. However, given such a small

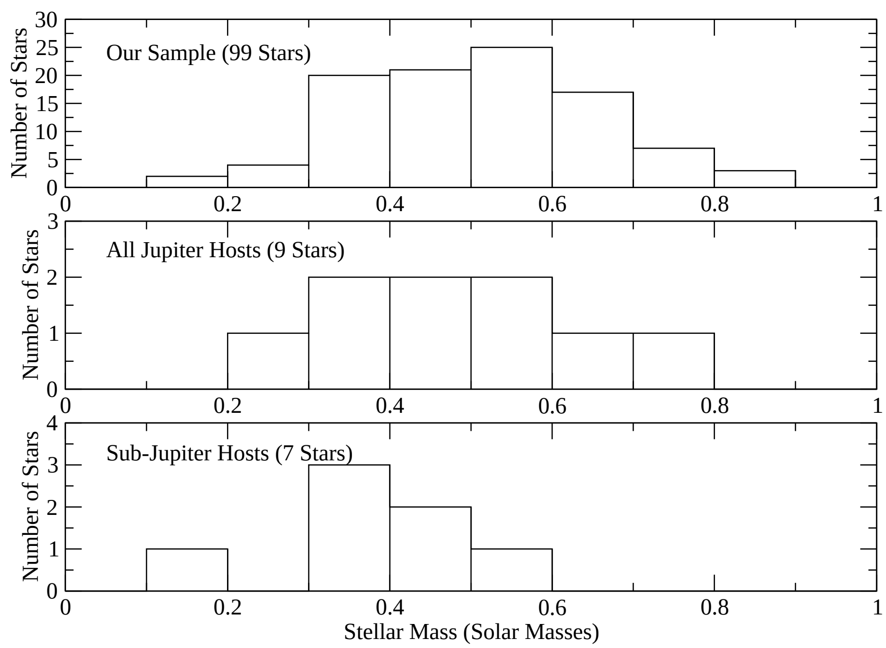

Figure 4.1: Histogram of stellar masses for our sample, compared with those of the known M dwarf planet hosts. The middle histogram shows all known Jovian hosts, while the third shows only the sub-Jupiter hosts without a Jovian planet.

number of planets, their result is vulnerable to biases. With a sample of 21 planets, we can make a more robust comparison between stellar and planetary mass, and begin to examine trends within the M spectral class. Figure 4.2 plots the masses of the M dwarf planets against the mass of their primary stars. While there is considerable scatter in the plot, there does appear to be a trend of increasing planet mass as stellar mass increases. This appears to extend the general result of Delfosse et al. (2006) to within the subcategory of M stars.

4.2 Stellar Metallicity

Obtaining metallicity estimates for M dwarfs is a difficult proposition. The complexity of their spectra makes calculating abundances through spectral analysis largely unreliable. To circumvent this issue, Bonfils et al. (2005, hereafter B05) identify M dwarfs in binary pairs with FGK stars, and calculate the [Fe/H] of both from the spectrum of the more massive primary, under the assumption that both stars formed from the same protostellar cloud. These binaries serve as a baseline for a photometric $V - K$ color versus absolute K-band magnitude calibration for M stars. Casagrande et al. (2008) utilize a similar scheme, but incorporate atmospheric models, and find results in agreement with the B05 technique.

Upon further examination, however, Johnson and Apps (2009, hereafter JA09), perform a calibration identical to that in B05 with a different sample, finding that the metallicity calibration in B05 underestimates the stellar [Fe/H]

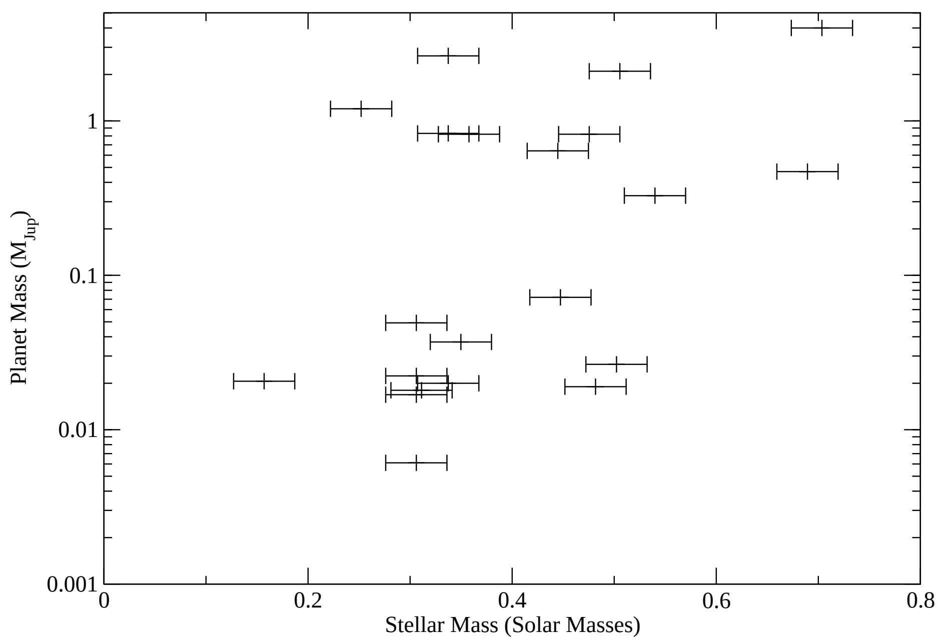

Figure 4.2: Masses of the known M dwarf planets and the masses of their parent stars.

by an average of -0.32 dex wherever [Fe/H] $>$ 0. The discrepancy is likely a result of an observational bias towards low-metallicity stars in the B05 sample. In light of this result, we calculate stellar metallicity using the JA09 calibration whenever possible. Adopting the standard notation, we use [M/H] to describe the overall heavy element abundance of a star. In the cases where a star's $(V-K)$ or M_K fell outside the ranges for which the JA09 calibration is valid, we used the B05 technique instead, since those stars almost uniformly tend to have low metallicites by any estimate.

Figure 4.3 again plots the distributions of our sample compared to those of the planet and Jupiter hosts, but shown against stellar metallicity. The average [M/H] of our sample, -0.02$\pm$0.3, falls between the averages of the M dwarf planet hosts with (0.22$\pm$0.4) and without (-0.07$\pm$0.07) Jovian planets, but all three sets have means within the errors of the others. What we can safely conclude from these distributions is that our sample is roughly evenly distributed around solar metallicity, so our results regarding planet fraction for M dwarfs should not have any systematic biases due to the metallicities of our targets.

Interestingly, the results of the K-S test for the metallicity distributions indicate relations between our targets and the set of M dwarfs with planets that are nearly opposite from those inferred from our stellar mass analysis. The probability of our sample and the published gas giant hosts being from the same abundance distribution is only 6 percent, but the probability increases to 93 percent when comparing our targets to the remaining planet hosts. Again,

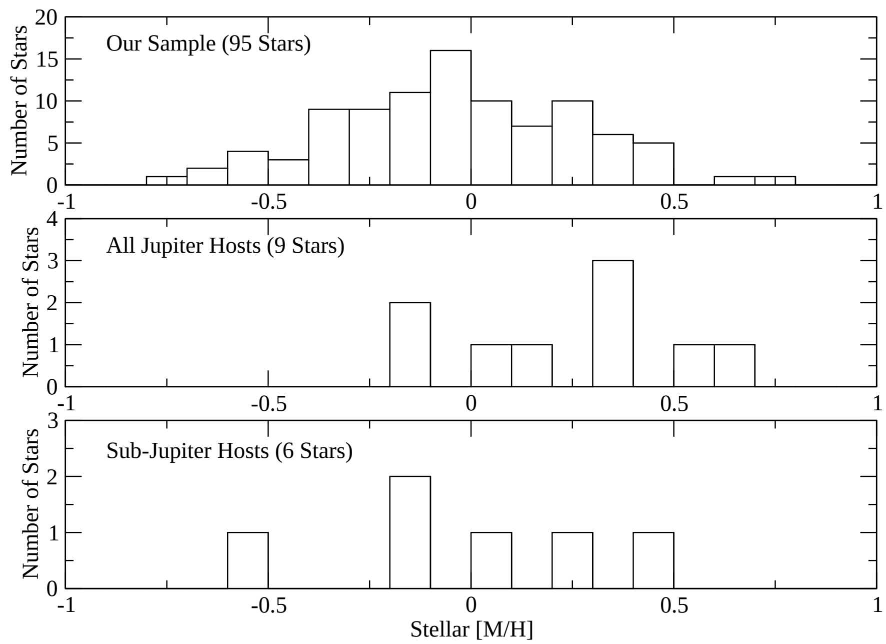

Figure 4.3: Histogram of stellar [M/H] for our sample, compared with those of the known M dwarf planet hosts. The middle histogram shows all known Jovian hosts, while the third shows only the sub-Jupiter hosts without a Jovian planet.

comparing the sets of Jovian and non-Jovian hosts to the overall distribution of M star planet hosts indicates correlation probabilities of 97 percent and 87 percent, respectively. These results strongly suggest that giant M dwarf planets are located preferentially around high-metallicity stars, confirming the analysis of JA09. On the other hand, our analysis suggests that M dwarfs may form lower-mass planets easily, even at roughly solar metallicity.

A plot of planet mass versus stellar [M/H] is shown in Figure 4.4. Despite the scatter, it is clear that there is a power-law dependence for this relation. Thus, while Jovian planets show evidence of being scarce around M dwarfs as a class, there appears to be an additional constraint that gas giant formation may be limited to high-metallicity M stars as well.

It is possible that the apparent planetary mass-stellar [M/H] relation could be due to one or more observational selection biases. By increasing the number of deep absorption lines in a star's spectrum, high abundance may simply make RV shifts more easily detectable, thereby increasing the number of planets discovered. M stars in general tend to have many lines regardless of metallicity, though, so the effect would probably be a small one. Given the large body of evidence that planet population increases with stellar metallicity, it may also be the case that observers have devoted a larger portion of their observing time to the stars with higher [M/H]. However, this is unlikely for several reasons. First, the low intrinsic luminosities of M stars cause planet searches in this regime to be apparent-magnitude limited; any consideration for metallicity would be completely secondary to brightness. Further, given the

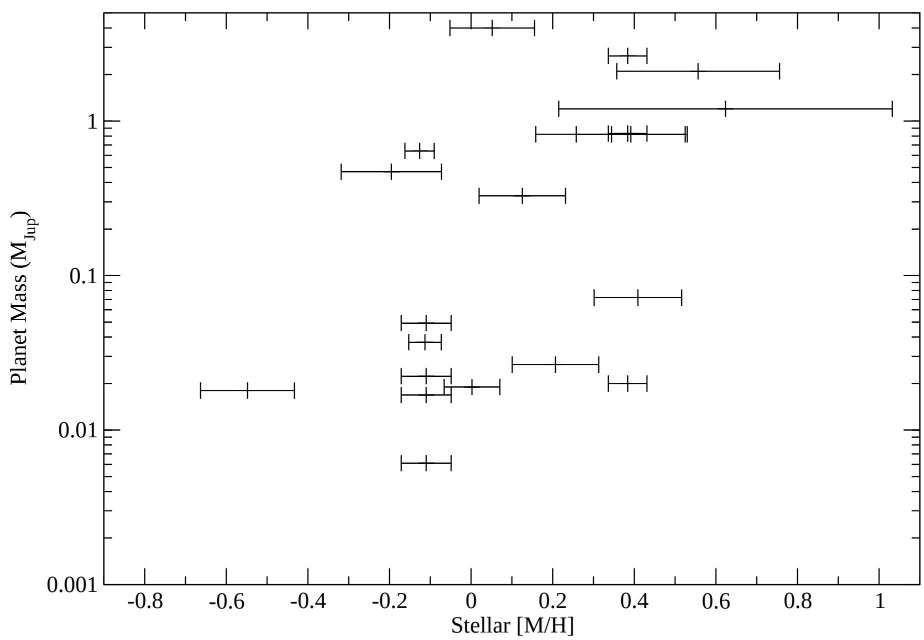

Figure 4.4: Masses of the known M dwarf planets and the [M/H] of their parent stars.

relatively recent development of reliable calibrations for M-dwarf metallicites, it is doubtful that any planet survey with an appreciable observational time baseline would have used [M/H] as a selection criterion for its target list. With these considerations in mind, we posit that the relation in Figure 4.4 is real, rather than a selection effect.

Chapter 5

Discussion

The stronger correlation to planet mass for stellar [M/H] as opposed to stellar mass does not necessarily suggest that metallicity is the primary factor responsible for the relatively low population of observed planets surrounding M dwarfs. Delfosse et al. (2006) show that the masses of M dwarf planets tend to be lower than those around G and K type stars, and Johnson et al. (2007) conclude that the fraction of stars with giant planets decreases with stellar mass for spectral types A-M. Additionally, M dwarf planet surveys are now complete enough to conclude that hot Jupiters should be extremely rare for M stars (see, e.g. Endl et al. 2006), indicating a reduced tendency for giant planets to either form or migrate around those stars relative to other main sequence stars. It is a natural conclusion, then, to assume that the lack of a convincing planet mass-stellar mass trend for these systems is simply due to the fact that the primary stars are confined to a very small range in mass, so that significant variation will not be observed.

Nevertheless, a growing amount of evidence suggests that metallicity is an important constraint on the formation of observable M dwarf planets, particularly for Jovian planets. The impact of metallicity is predicted in Ida and Lin (2005b), who claim that gas giant formation is a function of stellar [M/H] even in systems that experience significant disk mass loss due to photo-evaporation, as is expected to be the case for M dwarf disks. JA09 claim that M stars with planets tend to have higher abundances than those without, and the recently announced discovery of GJ 179b (Howard et al. 2010) appears to be in agreement with this conclusion. In a survey of metal-poor dwarfs, Sozzetti et al. (2009) find a strong metallicity dependence for the presence of Jupiter-type planets, a result consistent with simulations performed by Ida and Lin (2004). Similarly, Sousa et al. (2008) find that the ratio of Jupiter- to Neptune-mass planets in a system varies as a function of stellar metallicity, although their statistics for Neptunes is biased by M dwarf systems, for which they use the B05 [M/H] calibration. Our observed correlation between planet mass and stellar [M/H] appears to confirm these results, and suggests that the rarity of observable gas giants around M dwarfs is at least partially due to the fact that those planets will be confined only to the M stars with high abundances, as expected within the framework of the core accretion model.

It seems likely, then, that the best way to obtain a statistically significant sample of M dwarf planets is to locate the low mass, super-Earth planets around these stars. Laughlin et al. (2004) and Ida and Lin (2005a) predict that such planets will be more abundant around low-mass stars due to the differences in formation mechanisms for gas giants and rocky planets, but detection of planets in this mass range is obviously much more difficult. We demonstrate that the recently developed methods of analyzing time series

RV data, particularly the generalized L-S periodogram, offer significant improvement of our ability to detect the weak signals typical of terrestrial-type planets. These techniques will prove essential, as future detections will require increasingly longer time baselines, which will likely be accomplished through the use of multiple instruments. As more data continues to improve the detection limits of M dwarf planets, we anticipate the detection of more low mass planets will allow refinements of the current observed dependences of stellar properties on the characteristics of their planetary systems.

Chapter 6

Summary

We have implemented new techniques for obtaining and analyzing our time-series RV data for the Hobby-Eberly Telescope M-Dwarf Planet Search, and demonstrated that they offer considerable improvement not only for our own survey, but also for RV analysis in general. The increased precision these methods afford will be particularly useful for identifying the low-mass Neptune- and terrestrial-type planets, which theory and observation indicate should be dominant in the inner regions of M dwarf planetary systems.

With 21 M dwarf planets now confirmed, we present a preliminary statistical examination of correlations between the masses of these planets and the masses and metallicities of the host stars. Planetary mass shows a significant dependence on both parameters, and Jovian planets tend to exist preferentially in high-metallicity systems. Further observations are required to place definitive constraints on planet formation models based on these results, but our analysis appears to confirm that M dwarf planets follow the same general trends in relation to their parent stars as other spectral types.

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Vita

Paul Robertson was born in Philadelphia, Pennsylvania and grew up in Morganton, North Carolina. He received B.A. degrees in physics and mathematics from the University of North Carolina at Chapel Hill in 2008. As an undergraduate, he studied quasars and galaxy clusters with Wayne Christiansen and James Rose.

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When he isn't immersed in astronomy, Paul enjoys playing basketball, being outdoors, and experiencing the Austin music scene.

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