Planets Around Massive Subgiants

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Abstract. Compared to planets around Sun–like stars, relatively little is known about the occurrence rate and orbital properties of planets around stars more massive than 1.3 M\(_\odot\). The apparent deficit of planets around massive stars is due to a strong selection bias against early–type dwarfs in Doppler–based planet searches. One method to circumvent the difficulties inherent to massive main–sequence stars is to instead observe them after they have evolved onto the subgiant branch. We show how the cooler atmospheres and slower rotation velocities of subgiants make them ideal proxies for F– and A–type stars. We present the early results from our planet search that reveal a paucity of planets orbiting within 1 AU of stars more massive than 1.5 M\(_\odot\), and evidence of a rising trend in giant planet occurrence with stellar mass.

1. Introduction

A planet–bearing star can be thought of as a very bright, extremely dense remnant of a protoplanetary disk. After all, a star inherits its defining characteristics—its mass and chemical composition—from the same disk material that forms its planets. The physical characteristics of planet host stars therefore provide a crucial link between the planets we detect today and the circumstellar environments from which they formed long ago. Studying the relationships between the observed occurrence rate and orbital properties of planets as a function of stellar characteristics informs theories of planet formation, and also helps guide the target selection of future planet searches.

A wealth of recent work has demonstrated that planet occurrence is strongly correlated with chemical composition (Gonzalez 1997; Santos et al. 2004); metal–rich stars are 3 times more likely to host planetary companions compared to stars with solar abundances (Fischer & Valenti 2005). This finding can be understood in the context of the core accretion model. Increasing the metallicity of a star/disk system increases the surface density of solid material at the disk midplane, which in turn leads to an enhanced growth rate for protoplanetary cores (Ida & Lin 2004; Kornet et al. 2005).

Another factor that enhances the surface density of material in the disk midplane is its total mass. If the mass of circumstellar disks scales with the mass of the central star, then there should be an observed correlation between planet occurrence and stellar mass (Laughlin et al. 2004; Ida & Lin 2005; Kennedy & Kenyon 2007). In principle, testing this hypothesis is fairly simple: one need only measure the fraction of stars with planets over a wide range of stellar masses. However, in practice such a study is not so straightforward given the limited range of stellar masses encompassed by most planet searches.
Figure 1. Distribution of stellar masses for the target stars of the California and Carnegie Planet Search. The majority of the stars have masses between 0.7 $M_\odot$ and 1.3 $M_\odot$.

The difficulty can be seen in Figure 1 which shows the distribution of stellar masses for the target stars in California and Carnegie Planet Search (CCPS; Valenti & Fischer 2005), which is representative of most Doppler–based planet searches. Most of the stars in Figure 1 have masses between 0.7 $M_\odot$ and 1.3 $M_\odot$. In a decidedly non–Copernican twist of nature, it turns out that stars like our Sun are ideal planet search targets. Solar–mass G and K dwarfs are slow rotators, have stable atmospheres, and are relatively bright. The fall–off toward lower stellar masses is simply because late K– and M–type dwarfs are faint, making the acquisition of high–resolution spectra difficult without large telescope apertures (Butler et al. 2006; Bonfils et al. 2005; Endl et al. 2003).

The sharp drop at higher stellar masses is due to a separate observational bias. Stars with spectral types earlier than F8 tend to have rotationally broadened spectral features ($V \sin i > 50$ km s$^{-1}$; Galland et al. 2005), have fewer spectral lines due to high surface temperatures, and display a large amount of atmospheric “jitter.” Stellar jitter is excess velocity scatter due to surface inhomogeneities and pulsation, which can approach 50–100 m s$^{-1}$ for mid–F stars (Saar et al. 1998; Wright 2005). These features conspire to limit the attainable radial velocity precision for early–type dwarfs to $>50$ m s$^{-1}$, rendering exceedingly difficult the detection of all but the most massive and short–period planets.

One method to circumvent the observational limitations inherent to high–mass dwarfs is to observe these stars after they have evolved away from the main–sequence. After stars have expended their core hydrogen fuel sources their radii expand, and their atmospheres cool leading to an increase in the number of metal lines in the star’s spectrum. Stars crossing the subgiant branch also shed a large amount of angular momentum through the coupling of stellar winds to rotationally generated magnetic fields (Gray & Nagel 1985; Schrijver & Pols 1993; do Nascimento et al. 2000). The cooler atmospheres and slower rotational
velocities of evolved stars lead to an increased number of narrow absorption lines in their spectra, making them much better suited for precision Doppler surveys.

2. A Doppler Survey of Subgiants

There are a number of planet searches targeting evolved, intermediate-mass stars. To date, most surveys have focused on K–giants (Frink et al. 2002; Hatzes et al. 2005; Lovis & Mayor 2007; Niedzielski et al. 2007) and “clump giants,” or asymptotic giant branch stars (Sato et al. 2003; Setiawan et al. 2003; Liu et al. 2007). These programs have detected a total of 9 substellar companions orbiting intermediate-mass giants, demonstrating that planets do form and can be detected around stars more massive than $\sim 1.5 M_\odot$.

Over the past 3 years we have been conducting a Doppler survey of evolved stars at Lick and Keck Observatories. However, instead of targeting clump giants and K giants, we have focused on stars occupying the region of the H–R diagram between the main–sequence and red giant branch, known as the subgiant branch. Our sample is described by Johnson et al. (2006) and is summarized below.

The main part of our sample is comprised of 120 subgiant stars, which were selected from the Hipparcos catalog based on the criteria $2.0 < M_V < 3.5$, $0.55 < B − V < 1.0$, and $V < 7.6$ (ESA 1997). Our sample of subgiants is illustrated in an H–R diagram shown in Figure 2. Also shown are the search domains of other Doppler surveys containing evolved stars, along with the theoretical mass tracks of Girardi et al. (2002), assuming solar abundances ([Fe/H]=0.0).

Subgiants occupy an observational “sweet spot” in the H–R diagram. They exhibit relatively low levels of jitter, typically around 5 m s$^{-1}$, which is only a factor of 2 higher than G dwarfs (Wright 2005) and significantly lower than the 20 m s$^{-1}$ of jitter typical for giants (Hekker et al. 2006). Like K giants, they have shed most of their primordial angular momentum and exhibit slow rotation velocities, with $V \sin i < 5$ km s$^{-1}$. Also, theoretical mass tracks along the subgiant branch are well separated, allowing for unambiguous mass estimates. Our sample of stars spans a stellar mass range $1.2 < M_*/M_\odot < 2.2$, which nearly doubles the stellar mass domain of the CCPS sample.

Our planet search around subgiants has two primary goals. First, we wish to compare the orbital characteristics of planets around intermediate-mass stars to the large statistical ensemble of planets around lower-mass stars. Second, we wish to measure the fraction of stars with planets for stellar masses $M_* > 1.3 M_\odot$. To study the relationship between stellar mass and planet occurrence, we compare the planet fraction from our high-mass sample to that of the larger sample of FGK stars in the CCPS and the low-mass M dwarfs from the NASA Keck M Dwarf Planet Search (e.g. Butler et al. 2006).

1 An additional 5 substellar companions have been detected around solar-mass giants

2 Our full survey contains an additional 39 giant stars with $M_V < 2$ and $B − V < 0.85$. However, these stars proved to be unsuitable Doppler targets, with a high fraction of close binaries and jitter in excess of 30 m s$^{-1}$. We focus here only on the more stable subgiants.
Figure 2. H–R diagram illustrating the parameter space spanned by our sample of subgiants (circles). Also shown are the regions occupied by clump stars and K giants (hashed regions); the theoretical stellar mass tracks of Girardi et al. (2002) for [Fe/H]=0.0 (thin lines); and the zero-age main sequence (thick diagonal line).

3. Planet Detections and Characteristics

The first detection from our sample of subgiants was announced in Johnson et al. (2006): a short–period, Jovian planet orbiting the 1.28 M_☉ subgiant HD 185269 (see also Moutou et al. 2006). With an orbital period \( P = 6.838 \) d and eccentricity \( e = 0.3 \), HD 185269 b has one of the highest eccentricities among the sample of known “hot Jupiters.” The next batch of planets discovered from our sample orbit stars that are notably massive: HD 175541 (1.69 M_☉), HD 192699 (1.65 M_☉) and HD 210702 (1.85 M_☉; Johnson et al. 2007a). Following the theoretical mass tracks of these three massive subgiants back to the main sequence reveals that they began life as early type dwarfs, with spectral types ranging from A5V to A8V.

We have recently submitted for publication three additional long–period planet candidates orbiting the intermediate–mass subgiants \( \kappa \) CrB (=HD 142091; \( M_* = 1.80 \) M_☉), HD 167042 (1.65 M_☉), and HD 16175 (1.35 M_☉; Johnson et al. 2007, ApJ submitted). Figure 3 shows the distribution of semimajor axes and
Figure 3. Distribution of semimajor axes and eccentricities for planets around stars with $M_* < 1.5 \, M_\odot$ (filled circles) and subgiants with $M_* > 1.5 \, M_\odot$ (open pentagrams). All of the planets around the evolved A–type stars orbit beyond $\sim 1$ AU. On the other hand, the eccentricity distributions for the two sets of planets are comparable.

eccentricities of all known exoplanets orbiting stars with masses $M_* < 1.5 \, M_\odot$. Also shown in the figure are planets orbiting subgiants with masses $M_* > 1.5 \, M_\odot$, including the 5 systems announced from our survey, our two strongest unpublished candidates\(^3\) and two other planetary systems around massive subgiants: HD 82744 (Korzennik et al. 2000) and HD 5319 (Robinson et al. 2007).

While the eccentricities of planets around evolved A stars are very similar to those of planets around Sun–like stars, Figure 3 reveals a remarkable trend in the semimajor axes of planets around high–mass stars. Planets around evolved A stars ($M_* > 1.5 \, M_\odot$) reside preferentially in wide orbits at or beyond $\sim 1.0$ AU (Johnson et al. 2007b). This observed semimajor axis distribution of planets around high–mass stars differs significantly from that of planets around lower–mass stars, of which 51% orbit closer than 1 AU. This cannot be due to an observational bias, since Doppler shift measurements are most senstitive to giant planets in short–period orbits. While the radii of stars expand as they evolve away from the main sequence, the radii of subgiants are still small compared to

\(^3\)Both unannounced systems have false alarm probabilities less than 1%, but lack sufficient phase coverage for publication at this time.
Figure 4. The fraction of stars with Jovian planets as a function of stellar mass. The error bars represent the uncertainties from Poisson statistics. The box above each bin shows the number of stars with detected planets, \( N_{\text{HOSTS}} \), and the total number of target stars, \( N_{\text{STARS}} \).

4. Planet Occurrence vs. Stellar Mass

Our sample of subgiants covers a range of stellar masses complementary to the CCPS sample of FGK stars and the sample of low–mass stars in the NASA Keck M Dwarfs Planet Search. In Johnson et al. (2007a) we showed that an analysis of the planet occurrence rate in three coarsely–spaced mass bins reveals a rising trend with stellar mass (Figure 4). For this analysis, we selected target stars and planet candidates with uniform detection characteristics, namely stars with more than 8 observations, and planets with \( a < 2.5 \text{ AU} \) and \( M_P \sin i \geq 0.8 \text{ M}_\text{Jup} \).

The observed correlation between stellar mass and planet occurrence has important implications for planet formation theory, as well as for future planet search efforts. Stellar mass has now been identified as an additional signpost of planeticity, along with stellar metallicity, making A–type stars promising targets.
for ground–based imaging surveys as well as space–borne astrometry and transit missions.

5. Future Directions

The study of planets orbiting massive stars is still in its infancy, with only 17 systems currently known, compared to the 180 Sun–like and low–mass planet host stars discovered over the past decade (Butler et al. 2006). Firmer conclusions about the occurrence rate and orbital properties of planets around A–type stars will require a much larger sample of detections. We have recently expanded our Doppler survey of subgiants to include 300 additional stars at Lick and Keck Observatories. Our primary goal is to confirm the correlation between stellar mass and planet occurrence seen in Figure 4. If the ∼ 9% occurrence rate holds, we expect to find 20–30 new planets over the next 3 years. This will represent a significant increase in the number of planets orbiting evolved A stars, and will allow us to perform a more robust analysis of the effects of stellar mass on planetary eccentricities, semimajor axes and multiplicity.

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References

Bonfils, X., Forveille, T., Delfosse, X., Udry, S., Mayor, M., Perrier, C., Bouchy, F., Pepe, F., Queloz, D., & Bertaux, J.-L. 2005, A&A, 443, L15
Butler, R. P., Wright, J. T., Marcy, G. W., Fischer, D. A., Vogt, S. S., Tinney, C. G., Jones, H. R. A., Carter, B. D., Johnson, J. A., McCarthy, C., & Penny, A. J. 2006, ApJ, 646, 505
Butler, R. P., Johnson, J. A., Marcy, G. W., Wright, J. T., Vogt, S. S., & Fischer, D. A. 2006, PASP, 118, 1685
do Nascimento, J. D., Charbonnel, C., L`ebre, A., de Laverny, P., & De Medeiros, J. R. 2000, A&A, 357, 931
Endl, M., Cochran, W. D., Tull, R. G., & MacQueen, P. J. 2003, AJ, 126, 3099
ESA. 1997, VizieR Online Data Catalog, 1239, 0
Fischer, D. A. & Valenti, J. 2005, ApJ, 622, 1102

For the updated catalog of extrasolar planet and their parameters see http://exoplanets.org.
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Frink, S., Mitchell, D. S., Quirrenbach, A., Fischer, D. A., Marcy, G. W., & Butler, R. P. 2002, ApJ, 576, 478
Girardi, L., Bertelli, G., Bressan, A., Chiosi, C., Groenewegen, M. A. T., Marigo, P., Salasnich, B., & Weiss, A. 2002, A&A, 391, 195
Gonzalez, G. 1997, MNRAS, 285, 403
Gray, D. F. & Nagar, P. 1985, ApJ, 298, 756
Hatzes, A. P., Guenther, E. W., Endl, M., Cochran, W. D., Döllinger, M. P., & Bedalov, A. 2005, A&A, 437, 743
Hekker, S., Reffert, S., Quirrenbach, A., Mitchell, D. S., Fischer, D. A., Marcy, G. W., & Butler, R. P. 2006, A&A, 454, 943
Ida, S. & Lin, D. N. C. 2004, ApJ, 616, 567
—. 2005, ApJ, 626, 1045
Johnson, J. A., Butler, R. P., Marcy, G. W., Fischer, D. A., Vogt, S. S., Wright, J. T., & Peek, K. M. G. 2007a, ArXive-prints, 707
Johnson, J. A., Fischer, D. A., Marcy, G. W., Wright, J. T., Driscoll, P., Butler, R. P., Hekker, S., Reffert, S., & Vogt, S. S. 2007b, ApJ, 665, 785
Johnson, J. A., Marcy, G. W., Fischer, D. A., Henry, G. W., Wright, J. T., Isaacson, H., & McCarthy, C. 2006, ApJ, 652, 1724
Kennedy, G. M. & Kenyon, S. J. 2007, ArXive-prints, 710
Kornek, M., Bodenheimer, P., Różycka, M., & Stepinski, T. F. 2005, A&A, 430, 1133
Korzennik, S. G., Brown, T. M., Fischer, D. A., Nisenson, P., & Noyes, R. W. 2000, ApJ, 533, L147
Laughlin, G., Bodenheimer, P., & Adams, F. C. 2004, ApJ, 612, L73
Liu, Y. J., Sato, B., Zhao, G., Noguchi, K., Wang, H., Kambe, E., Ando, H., Izumiura, H., Chen, Y. Q., Okada, N., Toyota, E., Omiya, M., Masuda, S., Takeda, Y., Murata, D., Itoh, Y., Yoshida, M., Kokubo, E., & Ida, S. 2007, ArXive-prints, 709
Lovis, C. & Mayor, M. 2007, ArXive-prints, 706
Moutou, C., Loeillet, B., Bouchy, F., da Silva, R., Mayor, M., Pont, F., Queloz, D., Santos, N. C., Ségransan, D., Udry, S., & Zucker, S. 2006, A&A, 458, 327
Niedzielski, A., Konacki, M., Wolszczan, A., Nowak, G., Maciejewski, G., Gelino, R. C., Shao, M., Shectman, M., & Ramsey, L. W. 2007, ArXive-prints, 705
Robinson, S. E., Laughlin, G., Vogt, S. S., Fischer, D. A., Butler, R. P., Marcy, G. W., Henry, G. W., Driscoll, P., Takeda, G., & Johnson, J. A. 2007, ArXive-prints, 708
Saar, S. H., Butler, R. P., & Marcy, G. W. 1998, ApJ, 498, L153+
Santos, N. C., Izraelian, G., & Mayor, M. 2004, A&A, 415, 1153
Sato, B., Ando, H., Kambe, E., Takeda, Y., Izumiura, H., Masuda, S., Watanabe, E., Noguchi, K., Wada, S., Okada, N., Koyano, H., Maehara, H., Norimoto, Y., Okada, T., Shimizu, Y., Uraguchi, F., Yanagisawa, K., & Yoshida, M. 2003, ApJ, 597, L157
Schrijver, C. J. & Pols, O. R. 1993, A&A, 278, 51
Setiawan, J., Hatzes, A. P., von der Lühe, O., Pasquini, L., Nae, D., da Silva, L., Udry, S., Queloz, D., & Girardi, L. 2003, A&A, 398, L19
Valenti, J. A. & Fischer, D. A. 2005, ApJS, 159, 141
Wright, J. T. 2005, PASP, 117, 657