Extrasolar Planets: A Galactic Perspective

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Abstract.

The host stars of extrasolar planets tend to be metal-rich. We have examined the data for these stars for evidence of trends in other galactic parameters, without success. However, several ESP hosts are likely to be members of the thick disk population, indicating that planet formation has occurred throughout the full lifetime of the Galactic disk. We briefly consider the radial metallicity gradient and age-metallicity relation of the Galactic disk, and complete a back-of-the-envelope estimate of the likely number of solar-type stars with planetary companions with \(6 < R < 10\) kpc.

1. Introduction

Exploitation of major scientific discoveries tends to follow a familiar pattern. Immediately following the initial discovery, the main focus is on verification, testing the initial analysis against alternative explanations for the same phenomena. The second phase centres on consolidation, acquiring additional observations and/or improved theoretical data on particular phenomena. The third phase is reached with the discovery of sufficient observational examples to map out a substantial fraction of the phase space occupied by key parameters.

After only a decade, investigations of extrasolar planets have clearly entered the third stage. More than 145 planetary-mass companions are known around over 125 main sequence dwarfs and red giants. The overall properties of these planets are discussed elsewhere in this volume (see the reviews by Marcy and Mayor). It is now well established that the frequency of (currently-detectable) planetary systems increases with increasing metallicity of the parent star (see Valenti, this conference). Here, we concentrate on analysing other salient properties of the extrasolar planetary (ESP) host stars, looking for evidence of potential correlations.

2. Wide planetary-mass companions of low-mass dwarfs

Recent months have seen the imaging of low-mass companions to several young stars in the Solar Neighbourhood. Neuhauser et al (2005) have identified a faint, common proper motion (cpm) companion of GQ Lupi, a \(\sim 0.45M_{\odot}\) member of the Lupus I group (\(\tau \sim 1 - 2\)Myrs); the companion lies at a separation of \(\sim 100\) AU and has a likely mass between 1 and 42 Jupiter masses (\(M_{J}\)). Similarly,
Figure 1. Wide planetary-mass companions of low-mass dwarfs: total mass as a function of separation in binary systems (adapted from Burgasser et al, 2003). The crosses plot data for stellar binaries, while solid points identify systems with brown dwarf components; the solid line outlines a linear relation between maximum separation and total mass, while the dotted line plots $a_{\text{max}} \propto M_{\text{tot}}^2$. The stars mark the location of 2M1207AB, GQ Lupi and AB Pic AB.

Chauvin et al (2005b) have discovered a faint companion to AB Pic, a K2 dwarf, member of the ~30 Myr-old Tucana-Horologium association; the companion is ~245 AU distant, with a likely mass of 13-14 M_J. Finally, and most intriguingly, Chauvin et al (2004a) have shown that 2MASS J1207334-393254, a ~35 M_J brown dwarf member of the ~10-Myr-old TW Hydrae association, has a wide companion, separation ~60 AU, with a likely mass of only 2-5 M_J (see also Schneider, this conference).

Should we classify these low-mass companions as planets or brown dwarfs? In my opinion, all of these objects are brown dwarfs. The mass estimates themselves, based on evolutionary models, offer no discrimination, since, while they overlap with the planetary régime, it remains unclear whether they lie beyond a lower limit to the brown dwarf mass spectrum (if such exists). The large distance between each companion and its primary is a more telling parameter. There is little question that the Solar System planets formed from the Sun’s protoplanetary disk; it seems reasonable to apply the same criterion in categorising extrasolar planets. This test offers no discriminatory power at small separations, such as with the 11 M_J companion of HD 114762, which has an orbital semi-major axis of 0.3 AU. However, one might argue that disks are likely to have problems forming massive companions at large radii. Thus, it seems un-
likely that a 35$M_J$ brown dwarf would possess a protoplanetary disk sufficiently massive that it could form a 2-5 $M_J$ companion at a distance of 60 AU from the primary.

Nonetheless, this debate over terminology should not be allowed to obscure the significance of these discoveries, particularly 2M1207AB. Recent analyses show that the maximum separation of binaries in the field appears to correlate with the total mass (Burgasser et al, 2003). The newly discovered systems lie at the extremes of this distribution (Figure 1). 2M1207AB is particularly notable, with not only a projected separation, $\Delta$, four times higher than comparable brown dwarf binaries, but also a very low mass ratio, $q = \frac{M_2}{M_1} < 0.14$. All of these systems would be extremely difficult to detect at ages exceeding~$10^8$ years; thus, their absence among field binaries could reflect either dynamical evolution (and system disruption), or observational selection effects.

3. The planetary host stars

The overwhelming majority of planetary systems have been discovered through radial velocity surveys, with a handful of recent additions from transit surveys and microlensing programs. The radial velocity surveys focus on solar-like stars, for obvious reasons, so it is not surprising that most of the ESP hosts are late-F to early-K dwarfs; moreover, almost all lie within 50 parsecs of the Sun (Figure 2).
Figure 3. Companions mass as a function of separation for solar-type stars within 25 parsecs of the Sun; the dotted lines mark the effective limits of the planetary radial velocity surveys. The scarcity of systems with masses between 0.01 and 0.1 $M_\odot$ is the brown dwarf desert.

Approximately 90% of the solar-type stars within 25 parsecs of the Sun are included in either the UC or Geneva surveys, although only the UC survey has published a catalogue of non-detections (Nidever et al, 2001). Building on the local completeness of these surveys, Figure 3 shows the distribution of semi-major axes/projected separation as a function of mass for all known companions of solar-type stars within 25 parsecs of the Sun; the distribution clearly shows the brown dwarf desert, and provides the most effective demonstration that extrasolar planets are not simply a low-mass tail to the stellar/brown dwarf companion mass function.

3.1. Stars and planetary properties

Given the correlation between planetary frequency and metallicity, one might expect a bias towards higher mass planets in metal-rich stars; the current data, however, do not support that contention. This suggests that high metallicity acts as a trigger for planet formation, rather than playing a key role in the formation mechanism itself. Metal-rich systems ([m/H] > 0.1) do include a higher proportion of short-period, hot Jupiters, perhaps reflecting higher viscous drag in the protoplanetary disk (Sozzetti, 2004; Boss, this conference).

There is no obvious direct correlation between the mass of the primary star and the masses of planetary companions. Thus, the $\sim 0.35M_\odot$ M3 dwarf, Gl 876, has two planets with masses comparable to Jupiter. On the other hand, one might expect an upper limit to the mass distribution to emerge, simply because
lower mass stars are likely to have lower mass protoplanetary disks (see also Marcy, this conference).

### 3.2. Metallicities and the thick disk

Chemical abundance, particularly individual elemental abundance ratios, serves as a population discriminant for the ESP host stars. Halo stars have long been known to possess $\alpha$-element abundances (Mg, Ti, O, Ca, Si) that are enhanced by a factor of 2-3 compared to the Sun. This is generally attributed to the short formation timescale of the halo (Matteucci & Greggio, 1983): $\alpha$-elements are produced by rapid $\alpha$-capture, and originate in Type II supernovae, massive stars with evolutionary lifetimes of $10^7$ to $10^8$ years. In contrast, Type I supernovae, which are produced by thermal runaway on an accreting white dwarf in a binary system, have evolutionary timescales of 1-2 Gyrs. These systems produce a much higher proportion of Fe; thus, their ejecta drive down the $[\alpha/\text{Fe}]$ ratio in the ISM, and in newly forming stars.

Recent high-resolution spectroscopic analyses of nearby high velocity stars provide evidence that the thick disk is also $\alpha$-enhanced (Fuhrmann, 1998, 2004; Prochaska, 2000). The thick disk is the extended population originally identified from polar star counts by Gilmore & Reid (1983); current theories favour an origin through dynamical excitation by a major merger early in the history of the Milky Way (ref). With abundances in the range $-1 < [m/H] < -0.3$ (Figure 4, upper panel), the thick disk clearly formed after the Population II halo, but before Type I supernovae were able to drive up the iron abundance. Thus, the thick disk population almost certainly comprises stars from the original Galactic disk, which formed within the first 1-2 Gyrs of the Milky Way’s history.

What is the relevance of these observations to planet formation? Valenti & Fischer (2005) have recently completed abundance analysis of the high-resolution spectroscopic data acquired by the Berkeley/Carnegie radial-velocity survey. Their analysis includes measurement of the abundance of Ti, an $\alpha$-element. The lower panel of Figure 4 shows the distribution of the full sample as a function of [Fe/H], identifying stars known to have planets. Three of the latter stars have $\alpha$-abundances consistent with thick disk stars (HD 6434, 0.48$M_J$ planet; HD 37124, 0.75$M_J$; HD 114762, 11$M_J$), while three other stars (HD 114729, 0.82$M_J$; $\rho$ CrB, 1.04$M_J$; HD 168746, 0.23$M_J$) have intermediate values of $[\alpha/\text{Fe}]$. These results strongly suggest that, even though planets may be extremely rare among metal-poor halo stars (Gilliland et al, 2000), planetary systems have been forming in the Galactic disk since its initial formation.

### 3.3. Kinematics

Stellar kinematics are usually characterised using the Schwarzschild velocity ellipsoid; probability plots (Lutz & Upgren, 1981) allow one to compare stellar samples that include multiple components with Gaussian velocity distributions (see, for example, Reid, Gizis & Hawley, 2002). With the completion of the Geneva-Copenhagen survey of the Solar Neighbourhood (Nordström et al.,
Figure 4. $\alpha$-element abundances in nearby stars. The lower panel plots data for nearby stars from Fuhrmann (1998), where the solid triangles mark stars identified as members of the thick disk. The upper panel plots data from Valenti & Fischer’s (2005) analysis of stars in the Berkeley/Carnegie planet survey; the solid points mark stars known to have planetary companions. Three stars (identified in the text) are almost certainly members of the thick disk.
Figure 5. The velocity distribution of ESP host stars (right hand panels) compared with the velocity distribution of solar-type stars within 40-parsecs of the Sun.

2004), we have distances, proper motions, radial velocities and abundances\(^1\) for most solar-type stars within 40 parsecs of the Sun. There are 1273 stars within that distance limit with \(0 < (b - y) < 0.54\) and \(M_V \geq 4.0\); analysing their kinematics, we have

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-9.6, -20.2, -7.6; 38.8, 31.0, 17.0 \ \text{kms}^{-1})
\]

with an overall velocity dispersion, \(\sigma_{tot} = 52.7 \ \text{kms}^{-1}\).

There are 129 ESP hosts with accurate distances and space motions, and their mean kinematics are

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-4.0, -25.5, -20.4; 37.7, 22.9, 20.4 \ \text{kms}^{-1})
\]

with an overall velocity dispersion, \(\sigma_{tot} = 48.6 \ \text{kms}^{-1}\). All three stars identified as likely members of the thick disk (and two of the possible members) have high velocities (60 to 110 kms\(^{-1}\)) relative to the Sun.

The two velocity distributions are very similar. The total velocity dispersion of the ESP hosts is slightly lower than the field, mainly reflecting the higher proportion of old, metal-poor stars in the latter population (this also accounts for the lower value of \(\sigma_V\) for the ESP hosts). Interpreted in terms of the standard

\(^1\)One should note that the abundances in this catalogue are tied to the Schüster et al \(uvby\)-based metallicity scale, which has colour-dependent systematic errors (Haywood, 2002). Those systematic errors can be corrected.
stellar diffusion model, \( \sigma_{\text{tot}} \propto \tau^{1/3} \), the observed difference formally corresponds to a difference of only 20% in the average age. The relatively high mean motion perpendicular to the Plane is somewhat surprising, and may warrant further investigation. With that possible exception, however, the velocity distribution of ESP host stars is not particularly unusual, given the underlying metallicity distribution.

4. Planetary cartography in the Galaxy

The ultimate goal of these statistical analyses is to answer a simple question: How many stars in the Galaxy are likely to have associated planetary systems? While we are still far from being able to construct a reliable detailed model for the stellar populations in the Milky Way, there have been some initial studies, notably by Gonzalez, Brownlee & Ward (2001). Here, we briefly consider those models.

4.1. Abundance gradients and the Galactic Habitable Zone

Planetary habitability is likely to depend on many factors: distance from the parent star; the stellar lifetime; (perhaps) planetary mass, which may depend on the metallicity of the system; (perhaps) the presence of a massive satellite; the existence of plate tectonics; and (perhaps) the space motion of the system. In contrast, from the perspective of planet formation, the correlation between planetary frequency and metallicity is the only significant factor that has emerged from statistical analysis of the known ESP systems. Extending the present results beyond the Solar Neighbourhood requires modeling of both the radial abundance gradient and the age-metallicity relation of the Galactic disk.

Most studies assume a logarithmic radial abundance gradient; for example, Gonzalez et al (2001) adopt a gradient, \( \frac{\delta [m/H]}{\delta R} \), of -0.07 dex kpc\(^{-1}\). More recent analyses of intermediate-age Cepheids (Andrievsky et al, 2002) suggest a more complex radial distribution, with a flatter gradient in the vicinity of the Solar Radius, but steeper gradients outwith these limits. Figure 5a matches both distributions against \([O/H]\) abundances for HII regions (from Shaver et al, 1983); we also show current estimates for the Sun, and for the Hyades, Pleiades and Praesepe clusters. By and large, the data favour the complex gradient, but one should note that extrapolating the inner gradient implies unreasonably high metallicities at \( R < 4\)kpc. It is probably more reasonable to infer that we require more observations of metallicity tracers in the inner Galaxy.

The metallicity gradients plotted in the upper panel of Figure 6 are based on young objects - even the Cepheids are less the 109 years old. Thus, the distributions are characteristic of the average metallicity of stars forming in the present-day Galaxy. Clearly, there is a substantial distribution of metallicity among the stars in the Solar Neighbourhood, and one would expect comparable dispersions at other radii. Gonzalez et al (2001) address this issue by assuming an age-metallicity relation, \( \frac{\delta [m/H]}{\delta \tau} \) of 0.035 dex Gyr\(^{-1}\); they assume a small dispersion in metallicity (\(< 0.08\) dex). Note that this type of relation corresponds to a constant fractional increase in metallicity with time; that, in turn,
Figure 6. The upper panel plots oxygen abundance data for HII regions as a function of Galactic radius (open squares, data from Shaver et al., 1983). We also show the oxygen abundances for the Sun (solid square) and for the three nearest open clusters, the Hyades, Pleiades and Praesepe (solid triangles). The dotted line plots the abundance gradient adopted by Gonzalez et al. (2001); the solid line marks the composite gradient derived by Andrievsky et al. (2002) from Cepheid data. The lower panel plots the age-metallicity distribution derived by Valenti & Fischer (2005) for stars in the Berkeley/Carnegie radial velocity survey; solid points mark stars known to be ESP hosts. The pentagon marks the Sun.
requires either an increasing yield with increasing metallicity or an increasing star formation rate at a constant yield.

The lower panel of Figure 6 matches the Gonzalez et al age-metallicity relation against empirical results from Valenti & Fischer’s (2005) analysis of stars in the Berkeley/Carnegie survey; both ESP hosts and the Sun are separately identified. Unlike the classic Edvardsson et al (1993) analysis, there is a trend in mean abundance with age. Overall, the observations indicate a much broader dispersion in metallicity, at all ages, than assumed by Gonzalez et al (2001)\(^2\). As with the radial abundance gradient, further analysis is required before settling on reliable values of these parameters.

4.2. Planetary statistics in the Solar Circle

Given these caveats, what can we say about the likely distribution of planetary systems in the Milky Way? For the moment, any calculations must be restricted to regions relatively close to the Sun. However, Figure 6 suggests that the local metallicity distribution may well be representative of stars with Galactic radii between 6 and 10 kiloparsecs. Taking this as a working assumption, we can calculate a back-of-the-envelope estimate of how many solar-type stars in this annulus might have planetary companions.

In making this calculation, we identify solar-type stars as stars with luminosities \(4 < M_V < 6\); we assumed a density law

\[
\rho(R) = \rho_0 e^{(R-R_0)/h} e^{-z/z_0}
\]

where \(\rho_0 = 4.4 \times 10^{-3}\) stars pc\(^{-3}\), with 90% of the stars assigned to the disk and 10% to the thick disk; \(h = 2500\) pc; and \(z_0 = 300\) pc for the disk, and \(z_0 = 1000\) pc for the thick disk. We assume an overall planetary frequency of 6%.

Given those starting assumptions, Figure 7 shows the expected radial density distribution and the metallicity distribution of ESP hosts. In total, we predict that \(\sim 3.5 \times 10^7\) solar-type stars are likely to have gas giant planetary companions with \(a < 4\) AU. The space density increases with decreasing Galactocentric radius (density wins over surface area), and the metallicity distribution is approximately flat for \(-0.1 < [m/H] < 0.3\). ESP hosts are not uncommon in the Solar Circle.

5. Summary and conclusions

More than 130 stars are now known to harbour planetary systems. The correlation between planetary frequency and metallicity is now well established, and probably reflects nature rather than nurture. We have analysed the statistical properties of the current sample of ESP hosts, looking for other possible trends and biases. With the possible exception of a higher mean velocity perpendicular to the Plane, the planetary hosts appear to be unremarkable members of the Galactic Disk.

\(^2\)Note that the Sun, which lies at the mode of the local abundance distribution, is somewhat metal rich for its age.
Several ESP host stars show enhanced $\alpha$-element abundances and high velocities relative to the Sun, strongly suggesting that they are members of the thick disk. If so, this indicates that planet formation has been a constant presence in the Galactic Disk.

We briefly considered the radial abundance gradient and age-metallicity distribution of disk stars. Recent results suggest that the gradient is flatter in the vicinity of the Sun than the canonical value, but probably steepens at larger radii; there is relatively little reliable data for the inner disk, $R < 6$ kpc. The age-metallicity distribution of the Berkeley/Carnegie RV sample shows substantial dispersion at all ages. While the uncertainties in these parameters limit our ability to model the full Galaxy, we can use local statistics to estimate the planetary population in the vicinity of the Sun. We estimate that there are over $3.5 \times 10^7$ ‘RV-detectable’ planetary systems with Galactocentric radii in the range 6 to 10 kpc.

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**References**

Andrievsky, S. M., Kovtyukh, V. V., Luck, R. E., Lépine, J. R. D., Maciel, W. J., & Beletsky, Y. V. 2002, *Astr. Astrophys.*, 392, 491
