Bioastronomy 2002: Life Among the Stars
IAU Symposium, Vol. 213, 2004
R.P.Norris and F.H.Stootman (eds.)

How Unusual are Stars with Planets?

I. Neill Reid

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

Abstract. Comparative analysis of the parent stars of extrasolar planetary systems and the local disk population shows a strong trend for increasing frequency with increasing abundance. Approximately 4.5% of solar-abundance ($-0.15 < [m/H] \leq +0.15$) stars have detectable planetary-mass companions.

1. Introduction

As illustrated vividly by reviews at this conference (Tinney 2004; Marcy 2004), radial velocity surveys for extrasolar planets (ESP) have produced an explosion of results in a remarkably short time. Consequently, we can already start to examine the Galactic demographics of the ESP hosts - what are their statistical properties, and how do those properties compare with the underlying stellar population(s) as a whole? The ultimate goal of this exercise is the determination of the frequency of (habitable) planetary systems in the Galaxy, a key term in the Drake equation. This paper considers current results for two parameters: the abundance of heavy elements in the ESP host stars; and the distribution of their velocities relative to the local standard of rest.

2. Background

First, a definition. Astronomers have an engagingly simple approach to the periodic table of elements: there's hydrogen, helium, and everything else is a "metal" (or a "heavy element"). Thus, the "metallicity" of a star is the ratio between the number of all atoms which are not H or He (M) and the number of hydrogen atoms (H). This quantity is usually expressed logarithmically as a ration with respect to the solar value,

$$[m/H] = log_{10}[\frac{M}{H}_*)/\frac{M}{H}_\odot)]$$

so [m/H] = -1.0 corresponds to a heavy element abundance one-tenth that of the Sun. Metallicity is often written as [Fe/H], since iron has numerous absorption lines available for measurement, and, at least for disk stars, individual elemental abundances scale together.

Metallicity is clearly a key ingredient in planet formation. A 1 $M_\odot$ pre-solar nebula, [m/H]=0, has $10^{-4} M_\odot$ of refractory metals (Fe, Si, Mg, etc.),

https://doi.org/10.1017/S0074180900192952 Published online by Cambridge University Press

corresponding to only $\sim$ 100 Earth masses. Metals are produced by stars, so the average abundance, $\langle[m/H]\rangle$, has increased over the history of the Galaxy. However, it is important to bear in mind that there has always been a substantial dispersion about the mean; thus, the old open cluster NGC 6791 (age 6-12 Gyrs) is metal-rich ($+0.16 < [m/H] < +0.4$), while NGC 188 ($\sim$ 8 Gyrs), M67 ($\sim$ 5 Gyrs) the Pleiades (125 Myrs) and the Orion nebula (< 10 Myrs) all have essentially the same abundance as the Sun (4.5 Gyrs),

There are three main stellar populations. The halo is the oldest population (12-13 Gyrs.), made up of metal-poor ($-4 < [m/H] < -0.7$) stars in >20-kpc radius spheroidal distribution. This population contributes only a few percent of the total baryonic mass ($\sim 2 \times 10^9 M_\odot$). The Bulge is a complex population occupying the central 1-2 kpc. Finally, the Galactic disk is a flattened population, radius $\sim$ 12 kpc and thickness of a few hundred parsecs, with a total mass of $\sim 5 \times 10^{10} M_\odot$. The first disk stars formed $\sim$ 10 Gyrs ago and star formation continues to the present day. Disk stars have metallicities $-0.5 < [m/H] < +0.5$. All of the ESP hosts and almost all nearby stars ($d < 50$ pc) are members of the disk.

3. Results

Several previous studies (e.g., Gonzalez 1997; Santos, Israelian, & Mayor 2001) have compared the the metallicity distributions of ESP hosts against the local field stars. However, there are two key requirements which must be satisfied in such analyses:

- The reference sample must be unbiased and representative of the local disk population. Unfortunately, this requirement tends to receive short shrift in many Galactic structure studies.
- The techniques used to determine metallicity must be self-consistent. Numerous methods, ranging from high-resolution spectroscopy to broadband photometry, are available for determining chemical abundance in stars of different spectral types, but those methods can give systematically different results. Failure to account for those systematics can lead to biased and erroneous results.

The techniques employed here are described in Reid (2002). In brief, the reference sample consists of 486 FGK stars with absolute magnitudes in the range $2.0 \leq M_V \leq 7.0$ ($M_V(\odot) = 4.79$), colours of $0.5 \leq (B-V) \leq 1.0$ ($(B\text{-}V)_\odot = 0.6$) and distances $d < 25$ parsecs. Unlike all previous studies, this reference sample is complete and volume-limited. As a result, it provides an unbiased representation of the properties of the local disk. These limits embrace almost all the ESP host stars, so a comparison of statistical properties matches like with like. Moreover, 419 of the field stars (86%), and all save two ESP host stars, have Strömgren photometry, allowing self-consistent abundance determination - particularly since Haywood (2002) has recently produced an improved calibration of that system.

As of July 15 2002, eighty-eight nearby stars are known to have at least one planetary-mass companion. However, eight systems were selected for observation based on their known high metallicity, so we exclude them from the

https://doi.org/10.1017/S0074180900192952 Published online by Cambridge University Press

current comparison. Twenty-four of the 486 25-parsec stars (4.9%) have known planetary companions, and we have used that ratio to scale the metallicity distribution of the ESP hosts to match the local disk sample. Note that this is likely to be an underestimate of the true overall frequency, even allowing for current detection limits, since only ~ 85% of the 486 stars are currently being monitored for velocity variations.

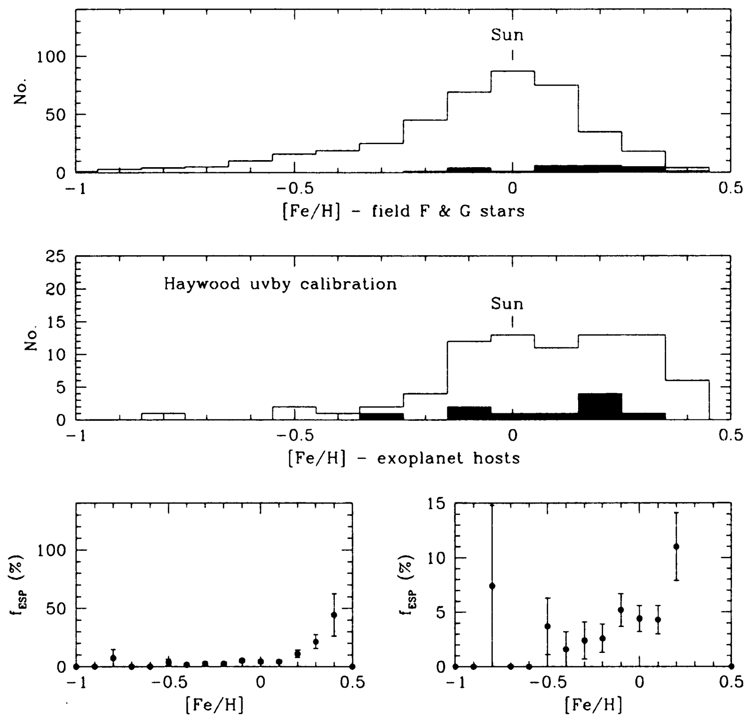

Figure 1. The fraction of currently-detectable ESP systems as a function of metallicity: the top panel plots the metallicity distribution of field star (the solid portion indicates the contribution from subgiant stars); the middle panel plots data for the known ESP host stars (omitting stars selected for observation based on [m/H]); the two lower panels plot the ratio (as a percentage), with different vertical scales.

There are two main results, illustrated in Fig. 1:

1. Contrary to many previous studies, the Sun occupies a nearly central position in the relatively compact disk metallicity distribution. 41% of the local disk dwarfs have [m/H]$\geq$ 0.0, while 93/419 (19%) have metallicities within $\pm$0.05 of the solar value.

2. There is a clear correlation between metallicity and the frequency of planetary systems detectable through current techniques. The detected fraction ranges from ~ 50% at [m/H]=+0.4 to ~ 2% at [m/H]=-0.4 dex. The one 'detection' at [m/H]=-0.8 is probably a brown dwarf (HD 111762).

https://doi.org/10.1017/S0074180900192952 Published online by Cambridge University Press

The observed correlation is clearly consistent with Gilliland et al. (2001) failure to detect any planetary transits in 47 Tucanae ([m/H]=-0.7), although the highly crowded environment in the halo globular cluster could also play a role in disrupting circumstellar disks. Planetary pollution of the outer stellar envelope has been suggested as a possible cause of the observed trend, but, as discussed by Santos, Israelian, & Mayor (2001) and Reid (2002), the absence of a correlation between $[m/H]_{max}$ and colour (depth of the stellar convective envelope) argues against this hypothesis. Our conclusion is that high-mass planets form more readily in metal-rich disks.

We can also compare the velocity distributions of the FGK field stars and the ESP hosts. Stellar motions are randomised through gravitational encounters with molecular clouds, so younger stars tend to have lower velocity dispersions than older stars. The ESP host stars have noticeably cooler kinematics than the FGK stars in the 25-parsec sample, suggesting an average age only 60% of the disk population as a whole.

4. Conclusions

Our analysis cleary shows a strong correlation between stellar metallicity and the frequency of a detectable planetary-mass companions - a correlation suggested previously, but quantified for the first time in this work.

Two important considerations must be borne in mind. First, we are considering planetary-mass companions detectable through current techniques, so our statistics can only provide a lower limit to the true planetary frequency. Second, even under those circumstances, the number of solar-like ($0.5 < (B-V) < 1.0$, $-0.15 < [m/H] < +0.15$) stars with known companions is large, even if the frequency is relatively low (4.5%). There are ~ 22.5 million solar-like stars within 50 parsecs of the disk mid-Plane and with Galactocentric distances of 7 to 9 kiloparsecs (± 1 kpc from the solar position); 10^6 of those stars should have planets detectable through current techniques.

References

Gilliland, R., et al. 2001, ApJ, 545, L47
Gonzalez, G. 1997, MNRAS, 285, 403
Haywood, M. 2002, MNRAS, in press
Marcy, G.M. 2004, this volume
Reid, I. N. 2002, PASP, 114, 306
Santos, N. C., Israelian, G., & Mayor, M. 2001, A&A, 373, 1019
Tinney, C. E. 2004, this volume