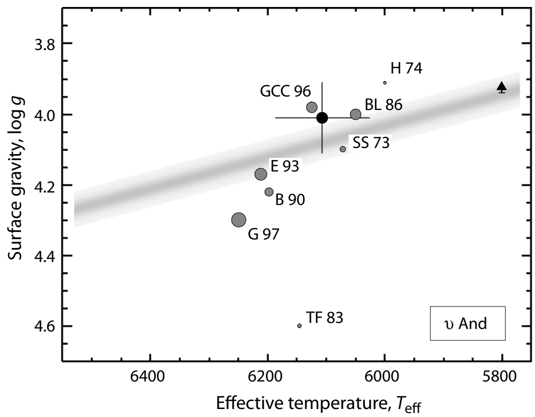

Figure 8.6: $\log g$ *versus* $T_{\rm eff}$ *for* υ *And. The black circle, with error bars, marks the spectroscopically derived values. The inclined greyscale bar indicates the most probable parameter space allowed by the accurate Hipparcos distance. Grey circles represent results from earlier work, with diameters proportional to derived metallicity. A systematic shift of the bar as a result of different metallicity scales is indicated by the vertical arrow for a decrease in [Fe/H] by 0.1 dex. From Fuhrmann et al. (1998, Figure 2), reproduced with permission © ESO.*

ing rapidly evaporated due to a high ultraviolet flux of their (presumably young and hot) host stars. From their chromospheric activity indices, none were found to be younger than 0.5 Gyr.

8.4 Element abundances

Chemical abundance analysis, using high-resolution high signal-to-noise spectroscopy, provides a fundamental diagnostic of host star properties, and an important if indirect probe of planetary formation and subsequent evolution.

8.4.1 Metallicity

An important aspact of a star's chemical composition is the fraction of *metals* (i.e. elements heavier than He in astronomy usage). Iron abundance, expressed as [Fe/H], is frequently used as the reference element for exoplanet host star studies (e.g. Fuhrmann et al., 1997, 1998; Gonzalez, 1997, 1998; Gonzalez et al., 1999; Gonzalez & Laws, 2000; Giménez, 2000; Murray et al., 2001; Santos et al., 2001; Murray & Chaboyer, 2002; Laws et al., 2003; Santos et al., 2003, 2004c, 2005, and others).

The abundances of other elements are providing increasingly valuable diagnostics (e.g. Gonzalez, 1998; Gonzalez & Vanture, 1998; Gonzalez & Laws, 2000; Santos et al., 2000; Gonzalez et al., 2001b; Smith et al., 2001; Sadakane et al., 2002; Zhao et al., 2002; Bodaghee et al., 2003; Ecuvillon et al., 2004a,b, and others).

Already from the earliest studies of just four systems (51 Peg, 55 Cnc, υ And, and τ Boo) it appeared that stars

Table 8.1: An incomplete list of some of the larger compilations of [Fe/H] relevant to exoplanet investigations, mostly for FGK dwarfs. The compilations often provide other parameters such as $\log g$ *and* $T_{\rm eff}$. $N_\star$ *is the total sample size,* $N_{\rm p}$ *is the number of planet stars hosts when quoted. References are for the latest descriptions in the case of progressively enlarged samples.*

$N_\star$	$N_{\rm p}$	Reference
3356	–	Cayrel de Strobel et al. (2001)
14 000	–	Nordström et al. (2004b)
1040	99	Valenti & Fischer (2005)
160	27	Takeda & Honda (2005)
100 000	–	Ammons et al. (2006)
216	55	Luck & Heiter (2006)
1907	–	Robinson et al. (2007)
118	28	Bond et al. (2008)
451	–	Sousa et al. (2008)

hosting planets have significantly higher metal content than the average solar-type star in the solar neighbourhood (Gonzalez, 1997). While the Sun and other nearby solar-type dwarfs have [Fe/H] ~ 0 (Reid, 2002), typical exoplanet host stars have [Fe/H] $\gtrsim$ 0.15. Values of [Fe/H] = +0.45 for two early discoveries, 55 Cnc and 14 Her, placed them amongst the most metal-rich stars in the solar neighbourhood (Gonzalez & Laws, 2000).

Although planets around even very low-metallicity stars have since been found, an overall correlation between metallicity and planet occurrence has been confirmed by subsequent work, using different samples and different analysis procedures.

Comparison stars Consistent agreement in determining effective temperatures and metallicities has proven notoriously difficult. Published results for a given star frequently formally disagree, as a combined result of differing spectral resolution, the choice of spectral lines, analysis procedures, and the adopted scales of metallicity and $T_{\rm eff}$. For the case of υ And shown in Figure 8.6, for example, nine publications pre-2000 give values spanning the range [Fe/H] = −0.23, $T_{\rm eff}$ = 6000 K (Hearnshaw, 1974) to [Fe/H] = +0.17, $T_{\rm eff}$ = 6250 K (Gonzalez, 1997).

To establish statistical differences between stars with and without planets at the level of 0.1–0.2 dex, a secure sample of comparison stars is required. The comparison sample should be demonstrably companion-free, and analyses for both samples should preferably be based on the same sets of spectroscopic lines, observed and analysed in the same way. A number of such spectroscopic host star samples and comparison sets have now been constructed and investigated.

Santos et al. (2001) first presented a spectroscopic study of a volume-defined set of 43 F8–M1 stars within 50 pc included in the CORALIE programme, and for which constant radial velocities over a long time interval provided evidence that the comparison stars are planet-free. A further 54 comparison stars were added by Santos et al. (2005), yielding two large and uniform samples of

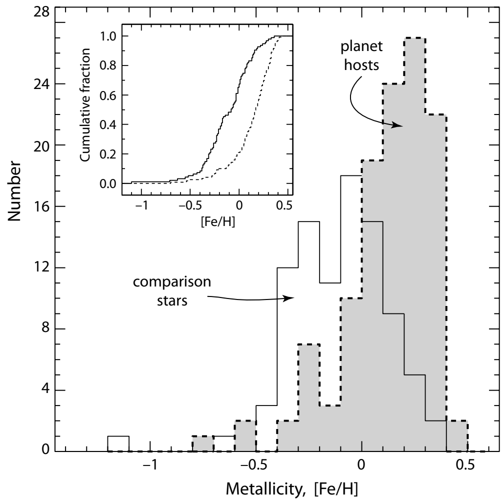

Figure 8.7: Metallicity distribution for 119 planet-host stars (shown as the dashed line, shaded), and for a volume-limited comparison sample of 94 stars with no known planets (continuous line, unshaded). The average metallicity difference of the two samples is 0.24 dex. Inset: cumulative distribution functions. A statistical Kolmogorov–Smirnov test shows that the probability that both distributions belong to the same population is $\sim 10^{-12}$. *From Santos et al. (2005, Figure 1), reproduced with permission © ESO.*

119 planet-host stars, and 94 stars without known planets, all of which have accurate stellar parameters and [Fe/H] estimates. These samples have been the basis of various subsequent abundance analyses (Santos et al., 2003; Bodaghee et al., 2003; Santos et al., 2004c; Israelian et al., 2004; Gilli et al., 2006). A further 64 comparison stars were added by Sousa et al. (2006).

Other large uniform spectroscopic surveys of exoplanet host stars and comparison stars include (see also Table 8.1): the 99 planet host stars from the 1040 FGK dwarfs of the Keck, Lick, and AAT programme, selected according to magnitude, colour, and luminosity (Valenti & Fischer, 2005); the 27 planet host star and 133 comparison stars observed at Okayama (Takeda et al., 2005; Takeda & Honda, 2005); the 28 planet host stars and 90 comparison stars from the Anglo–Australian planet search programme (Bond et al., 2006, 2008); and the 216 star sample of the 'nearby stars project' (Heiter & Luck, 2003; Luck & Heiter, 2005, 2006).

Luck & Heiter (2006) detail the overlap between these and other samples, including the extensive Geneva–Copenhagen spectroscopic and kinematic survey (Nordström et al., 2004a,b).

Occurrence versus metallicity A comparison based on the host star and control samples of Santos et al. (2005) confirmed previous indications that the frequency of giant planets rises as a function of [Fe/H] (Figure 8.7). Similar results were found by Fischer & Valenti (2005), who gave the incidence of Doppler-detected giant planets as < 3% for [Fe/H] < −0.5, and 25% for [Fe/H] > +0.5. Over the range −0.5 < [Fe/H] < 0.5, and for FGK-type main-sequence stars, they expressed the probability of formation of a gas giant planet, with orbital period shorter than 4 yr and $K > 30\,\mathrm{m\,s^{-1}}$, as

$$\begin{aligned} P(\text{planet}) &= 0.03 \times 10^{2.0[\mathrm{Fe/H}]} \\ &= 0.03 \left[\frac{N_{\mathrm{Fe}}/N_{\mathrm{H}}}{(N_{\mathrm{Fe}}/N_{\mathrm{H}})_\odot} \right]^2 , \end{aligned} \tag{8.16}$$

the second expression following from the definition of [Fe/H] (box on page 186).

As discussed further below, the correlation between occurrence and metallicity may not extend to giant stars, to stars of intermediate metallicity, to M dwarfs, or to the occurrence of low-mass planets.

Transiting planets The correlation between metallicity and occurrence appears to extend to the close-in giant planets discovered by transit photometry.

To explain the observed radius anomalies for transiting planets known at the time (including HD 209458 and OGLE–TR–10 considered to be anomalously large, and HD 149026 considered to be anomalously small), Guillot et al. (2006) suggested an exoplanet composition/evolution model which included an additional internal energy source equal to 0.5% of the incoming stellar luminosity. This additional heat source acts to slow the cooling of the planet.

With this adjustment to bring the radii into better consistency with theoretical models, they showed that for the nine transiting planets known at the time, the amount of heavy elements that had to be added to match their observed radii was a steep function of the host star metallicity: from less than $20M_\oplus$ of heavy elements around stars of solar composition, to up to $100M_\oplus$ for stars with three times the solar metallicity (Figure 8.8). These results add to the picture that heavy elements play a key role in the formation of close-in giant planets.

A uniform determination of spectroscopic parameters for 13 host stars of transiting planets was made by Ammler-von Eiff et al. (2009), and supplemented by a compilation of results for a total of 50 transit host stars. A systematic offset in the abundance scale was found for the TrES and HAT objects.

Giant stars Pasquini et al. (2007) found that planet occurrence around a sample of 14 giant stars does not correlate with increasing metallicity, in contrast with main sequence stars. While they favoured an explanation based on the accretion of metal-rich material (§8.4.3), other interpretations are also possible, perhaps due to differences in migration, or to the presence of a dual-formation mechanism (Matsuo et al., 2007) with a metal-independent mechanism more effective for large

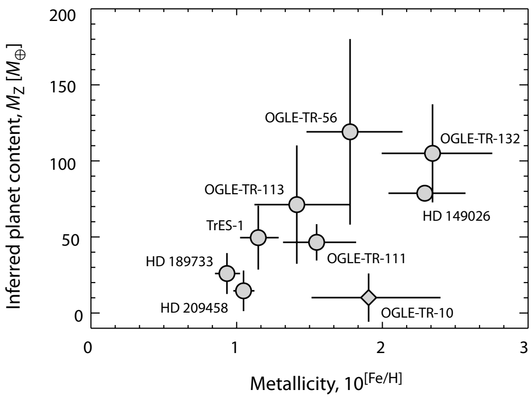

Figure 8.8: Mass of heavy elements in the transiting planets as a function of the metal content of the host star. The mass of heavy elements is that required to fit the observed radii, calculated on the basis of evolution models including an additional heat source assumed equal to 0.5% of the incoming stellar heat flux. From Guillot et al. (2006, Figure 3), reproduced with permission © ESO.

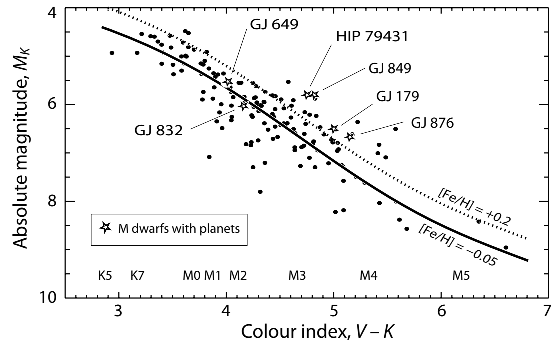

Figure 8.9: Nearby low-mass stars from the Keck sample in the M_{K_s} versus $V-K_s$ plane, with the corresponding spectral types shown at bottom. Small black circles indicate a volume-limited sample of single K dwarfs ($d<20$ pc) and M dwarfs ($d<10$ pc). The solid line is a fifth-order polynomial fit to the mean main sequence, and corresponds to roughly solar metallicity. Open symbols indicate all M dwarfs known to harbour at least one giant planet. From Johnson et al. (2010c, Figure 1), reproduced by permission of University of Chicago Press.

stellar masses. The choice of metallicity scale may also be a contributing factor (Santos et al., 2009). A similar trend was found for 322 late-G giants, including 10 planet host stars, by Takeda et al. (2008b).

Stars of intermediate metallicity Haywood (2008) used α-element abundances, and the Galactic velocity components (notably the component V in the direction of Galactic rotation), to classify the fourteen exoplanet host stars in the metallicity range −0.7 to −0.2 dex according to their membership of the thin disk or thick disk populations. All but one belong to the thick disk, and just one to the metal-poor tail of the thin disk. A similar result for older, lower metallicity host stars with enhanced [α/Fe] had been noted by Reid et al. (2007).

The classification by population is possible because, at these intermediate metallicities, stars in the solar vicinity fall into two main groups: the thin disk being solar in α-elements and rotating faster than the *local standard of rest* (viz. the velocity of a hypothetical group of stars in strictly circular orbits at the solar position), while the thick disk is enriched in α-elements, [α/Fe] >0.1 dex, and lags the local standard of rest.

The distinct properties of the thin and thick disk in terms of α-element enrichment as a function of metallicity are illustrated in the studies of e.g. Fuhrmann (1998), and Reddy et al. (2003, 2006).

M dwarfs The complex spectra of low-mass M dwarfs precludes the use of standard LTE spectroscopic modeling, and the knowledge of their metallicity distribution has been based until recently on photometric calibration (Bonfils et al., 2005a). This calibration originally suggested that M dwarfs in the solar neighbourhood, including those with known planets, are systematically metal poor compared to their higher-mass counterparts (Bean et al., 2006).

Johnson & Apps (2009) derived a revised metallicity calibration based on $V-K_s$ photometry of a volume-limited sample with common proper motion companions and found that, in contrast, M dwarfs with planets appear to be systematically metal rich. The mean metallicity for their M dwarf sample with planets is Fe/H = +0.16, compared with +0.15 for the FGK dwarfs with planets. The result brings the M dwarfs into a consistent pattern of metallicity excess being correlated with planet occurrence. There is still a systematically lower fraction of Jovian planets around M dwarfs than FGK dwarfs at any given metallicity, a result likely to be a reflection of their lower stellar masses, rather than an effect of metallicity.

By late 2010, seven Doppler-detected giant planets were known around six M dwarfs (Figure 8.9). From their volume-limited Keck sample, Johnson et al. (2010c) estimate that $3.4^{+2.2}_{-0.9}$% of stars with $M_\star < 0.6 M_\odot$ host planets with $M \sin i > 0.3 M_{\rm J}$ and $a < 2.5$ AU. Restricted to metal-rich stars with [Fe/H] > +0.2, the occurrence rate rises to $10.7^{+5.9}_{-4.2}$%.

Neptune-mass planets The first Doppler detections of low-mass planets already suggested that their occurrence might show a different dependence on the host star metallicity than the case for giant planets (e.g. Udry et al., 2006).

Sousa et al. (2008) derived [Fe/H] for 451 stars from the HARPS high-precision sample. They found that, in contrast to the giant Jupiter-mass planets, Neptune-like planets do not form preferentially around metal-rich stars, with the ratio of Jupiter to Neptune mass planets being an increasing function of metallicity. The number of Neptune mass planets is currently only small, and most hosts with only Neptune-mass planets are in any case M dwarfs.

8.4.2 Possible biases

That the planetary occurrence trend versus metallicity might arise from a variety of observational biases has been considered in some detail. Specific sample selection criteria certainly affect the resulting statistics, although the studies cited below suggest that none of the possible effects identified is likely to explain the observed probability–metallicity correlation.

Selection bias Most radial velocity surveys are biased against very young stars with their higher rotational velocities or higher chromospheric activities, effects quantified in this context by Paulson & Yelda (2006). They are also biased against multiple star systems, and against metal poor stars, although the latter are in any case only poorly represented in the solar neighbourhood.

Magnitude-limited and volume-limited surveys result in different representations of stars of different spectral types, as discussed by Fischer & Valenti (2005). But even the distance-limited criterion of Santos et al. (2005) is not a volume-limited survey, since their sample of F8–M1 stars within 50 pc does not include all late G, K, and M dwarfs within that distance.

A more subtle bias against low-mass high-metallicity stars results from a magnitude cut-off, while a colour cut-off gives the opposite (Murray & Chaboyer, 2002).

Orbital period bias Radial velocity surveys are themselves biased in detecting planets with shorter orbital periods and larger masses. The observed metallicity correlation could therefore reflect a dependence of orbital radius on metallicity, perhaps signaling a dependence of migration rate on metallicity (Gonzalez, 2003; Sozzetti, 2004; Gonzalez, 2006a).

Observationally, the weak correlation between metallicity and orbital period first reported by Sozzetti (2004) has not been confirmed. In later studies with larger samples, there is no evident correlation between metallicity and semi-major axis (Fischer & Valenti 2005, their figure 15; Jones et al. 2008b, their figure 6.8), nor indeed with eccentricity or planet mass (Bond et al., 2008, their figure 4).

Neither is there any theoretical expectation yet invoked of a link between metallicity and migration rate (Livio & Pringle, 2003). Pinotti et al. (2005) have proposed a model that correlates the metallicity of the host star with the semi-major axis of its most massive planet prior to migration. Further out, the formation of debris-generating planetesimals at tens of AU may still be independent of the metallicity of the primordial disk (Greaves et al., 2006).

In summary, there remains the possibility that the majority of giant planets currently known have experienced significant migration, and therefore that current Doppler surveys still sample only a specific subset of the overall exoplanet population.

8.4.3 Origin of the metallicity difference

Excluding the possibility of selection bias, two principal hypotheses have been put forward to explain the connection between high metallicity and the presence of massive planets: either causative as a consequence of higher primordial abundances facilitating accretion, or by self-enrichment as a result of the capture of metallicity-enhanced material. Based on the additional evidence described below, the current consensus is that while some host stars may be polluted to some degree by material capture, the dominant effect is likely to be primordial, with planets simply more likely to form around metal-rich stars.

However, the anomalies noted above – the absence of a similar correlation for giant stars, for low-mass planets, and for stars of intermediate metallicity – point to the picture being incomplete. A collective explanation may lie in the possible migration of giant planet hosts from the inner regions of the Galaxy. These various possibilities are considered further in this section.

Primordial occurrence According to this hypothesis, the high metallicity observed in certain hosts is a bulk property of the star, and represents the original composition out of which the protostellar and protoplanetary molecular clouds formed.

In this picture, the higher the metallicity of the primordial cloud, the higher the proportion of dust to gas in the protoplanetary disk. This facilitates condensation and accelerates protoplanetary accretion before the gas disk is lost (Pollack et al., 1996). Giant planets are subsequently formed by runaway accretion of gas onto such rocky cores with $M \sim 10 M_\oplus$, rather than by gravitational instabilities in a gaseous disk which predicts formation much less sensitive to metallicity (Boss, 2002). The cut-off in the metallicity distribution for host stars at [Fe/H] $\gtrsim 0.5$ (Figure 8.7) then represents the upper limit to metallicities in the solar neighbourhood.

Observationally, the probability of forming a giant planet appears to be proportional to the square of the number of Fe atoms (Equation 8.16). Since particle collision rates are similarly proportional to the square of the number of particles, this result has been further used to argue a physical link between dust particle collisions in the primordial disk and the formation rate of giant planets. Based on the core accretion model, Kornet et al. (2005), Wyatt et al. (2007), and Ida & Lin (2004b, 2005a) were able to reproduce the distribution of giant planets with host star metallicity. The latter model also predicts that short-period giant planets should be rare around M dwarfs, but that Neptune mass ice-giant planets might be common, a trend which is broadly apparent in M dwarf Doppler surveys (Endl et al., 2006).

If metallicity determines the time scale for giant planet formation, there should be a correlation between planet mass and metallicity. Rice & Armitage (2005) showed some evidence for this correlation, although the same trend is not evident in the studies of, e.g., Bond et al. (2008, their Figure 4).

Self-enrichment An alternative explanation is that the high metallicity is a phenomenon restricted to the surface region of the star, arising from the capture of metal-rich material, and the resulting 'pollution' of its outer convective envelope. This might be the result of the terminal inward migration of a planet onto the star as a result of dynamical friction (Laughlin & Adams, 1997; Gonzalez, 1998; Siess & Livio, 1999b; Israelian et al., 2001; Sandquist et al., 2002; Israelian et al., 2003), self-pollution due to the transfer of gas-depleted, metal-rich material from the disk to the star as a result of migration (Goldreich & Tremaine, 1980; Lin et al., 1996; Laughlin, 2000; Gonzalez et al., 2001b), or to the break-up and infall of planets or planetesimals onto the star due to gravitational interactions with other companions (Rasio & Ford, 1996; Queloz et al., 2000b; Quillen & Holman, 2000; Quillen, 2002).

A planet added to a fully convective star would be folded into the entire stellar mass, and would lead to a negligible overall metallicity enhancement. However, main sequence solar mass stars like the Sun have radiative cores with relatively small outer convection zones comprising only a few percent of the stellar mass. At ages of $\gtrsim 10^8$ yr the Sun's outer convection zone had reduced to $\sim 0.03M_\odot$ (Ford et al., 1999, and Figure 8.10). For higher mass stars, the convection zone is smaller still ($0.006M_\odot$ at $1.2M_\odot$), so that the sensitivity of surface metallicity to accreted matter rises steeply for stars more massive than the Sun.

Under these conditions, planet capture could significantly enhance the heavy element content in the convective zone, resulting in elemental abundances deviating from the underlying trends resulting from Galactic chemical evolution (Figure 8.10). Planet hosts having the shallowest convection zones would be expected to have the highest metallicities (Laughlin & Adams, 1997; Ford et al., 1999; Siess & Livio, 1999b; Pinsonneault et al., 2001; Li et al., 2008b).

Studies have pursued various implications of the self-enrichment model. Murray & Chaboyer (2002) estimated that some $5M_\oplus$ of iron would have to be slowly accreted over some 50 Myr to explain the observed mass–metallicity and age–metallicity relations. Sandquist et al. (1998) showed that a capture event may also influence the further orbital migration of other

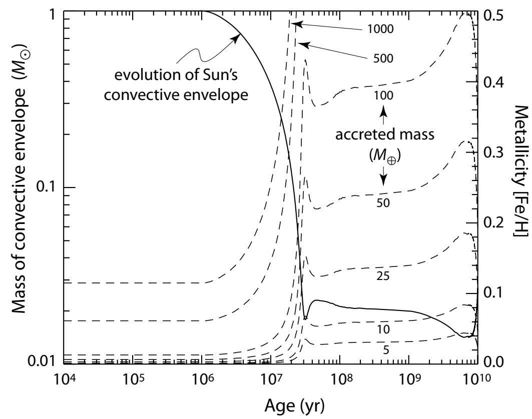

Figure 8.10: High metallicity arising from pollution. The solid line (left axis) shows the evolution of the Sun's convective envelope. Dashed lines (right axis) indicate the surface metallicity that would result from the instantaneous accretion of rocky material onto the star at each time in the Sun's past (masses in $M_\oplus$), assuming that the accreted material is mixed throughout the convective envelope. Producing high surface metallicities of 0.2–0.3 dex is possible with the accretion of $\sim 10 - 25M_\oplus$ of rocky material after 10^7 yr. From Ford et al. (1999, Figure 5), reproduced by permission of the AAS.

planets in the system due to changes in angular momentum or magnetic field. Sandquist et al. (2002) argued that an infalling planet could penetrate the convection zone. Cody & Sasselov (2005) developed a stellar evolution code to model stars with non-uniform metallicity distributions, motivated by the phenomenon.

One important test of the enrichment hypothesis makes use of the fact that when a star leaves the main sequence, its convection zone deepens significantly. This would lead to strong dilution if the high metallicity is a result of surface pollution. Fischer & Valenti (2005) used their sample of 1040 nearby FGK dwarfs (Valenti & Fischer, 2005), including 99 planet hosts, to show that there is no correlation between planet host metallicity and the convection zone depth, either while the star is on the main sequence, or after it evolves to the subgiant branch and its convection zone deepens (Figure 8.11). This result has been taken to support the primordial basis of the observed correlation.

Another test of self-enrichment is to search for compositional differences between common proper motion pairs (i.e. binary components with large separations), which presumably formed together out of the same molecular cloud with the same chemical composition. Accretion has been invoked to explain abundance anomalies in the binary 16 Cyg A and 16 Cyg B (where the planet orbits the B component), which have very different Fe abundances and Li content (Gonzalez, 1998; Laws & Gonzalez, 2001). Similar arguments were given for HD 219542 (Gratton et al., 2001), although the exoplanet host status of the latter was subsequently re-

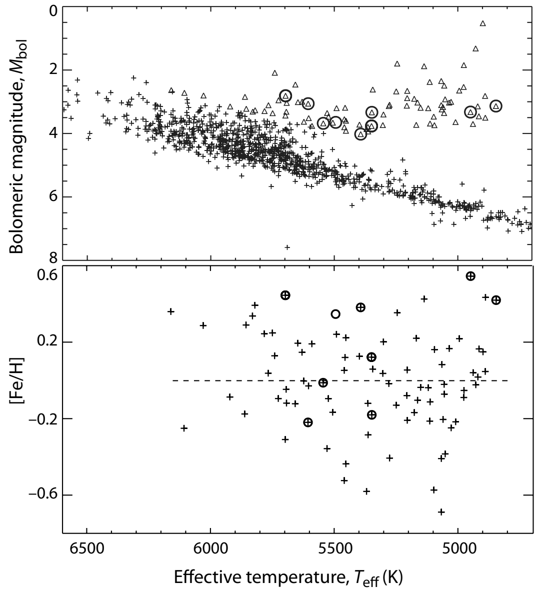

Figure 8.11: Top: Hertzsprung–Russell diagram for stars from the Keck, Lick, and AAT planet search projects, as of 2005. Key: + = main sequence stars; △ = subgiants ($M_{\rm bol}$ > 1.5 mag above the lower main sequence boundary); circled symbols: subgiants with detected planets. Bottom: subgiants, with detected planets circled. If the high metallicity correlated with the presence of Jovian planets is limited to the convective envelope of main sequence stars, subgiants with planets should show progressively lower metallicity as a result of dilution as they evolve across the subgiant branch. No such gradient is observed. From Fischer & Valenti (2005, Figures 11–12), reproduced by permission of the AAS.

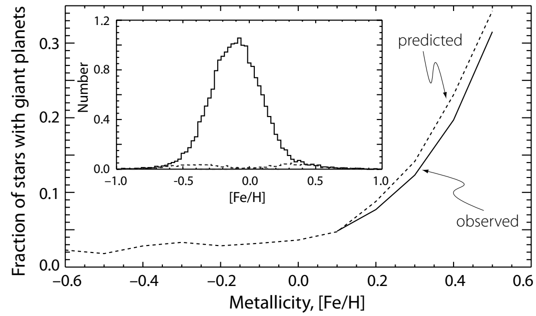

Figure 8.12: Inset: the simulated 'local' metallicity distribution (main histogram). The contributions of the metal-rich and metal-poor components assumed to have come to the solar neighbourhood by radial migration are shown by the lower dashed line. Main: the predicted fraction of stars with giant planets obtained assuming the metallicity distribution and intrinsic giant planet proportion of 0% in the metal-poor component, 5% locally, and 25% in the metal rich component (dashed line). The solid line is the fraction of planet hosts versus stellar metallicity according to Udry & Santos (2007). From Haywood (2009, Figure 4b), reproduced by permission of the AAS.

tracted (Desidera et al., 2003). Fifty common proper motion pairs were studied by Desidera et al. (2004) and Desidera et al. (2006), and nine pairs by Luck & Heiter (2006). The implications for the reported differences remains unclear.

Other evidence for accretion has been attributed to the presence of ^{6}Li, discussed further in §8.4.7, in the metal-rich dwarf HD 82943 (Israelian et al., 2001, 2003), in 59 Vir (Fuhrmann, 2004), in non-planet hosting stars including the super-lithium-rich F dwarf J37 in NGC 6633 (Laws & Gonzalez, 2003; Ashwell et al., 2005), and for various white dwarfs (Jura, 2006).

Notwithstanding what is now a general consensus that the occurrence–metallicity correlation is essentially primordial, material accretion would appear to be an inevitable by-product of planet formation and evolution. Certainly, the Sun continues to accrete cometary material today: accretion of up to $100 M_\oplus$ of metal-rich material was proposed as a partial resolution of the solar neutrino problem (Jeffery et al., 1997), but such a mass is probably ruled out by solar models, where the differences between solar photospheric and meteoritic abundances display a weak but significant trend with condensation temperature, suggesting that the metallicity of the Sun's envelope has been enriched relative to its interior by about 0.07 dex (Gonzalez, 2006b).

Different Galactic origins As noted above, the correlation between stellar metallicity and the occurrence of giant planets appears to break down for giant stars, and for stars of intermediate metallicity for which giant planets are found preferentially orbiting thick disk stars. Haywood (2008, 2009) has suggested that the explanation underlying the giant planet occurrence–metallicity correlation is a dynamical manifestation related to the migration of stars in the Galactic disk. Giant planet formation is then hypothesised to correlate with Galactocentric distance, rather than being primarily linked to metallicity, according to the following picture.

Most metal-rich stars (Fe/H > +0.25 dex) found in the solar neighbourhood, including those hosting planets, are considered to have migrated from the inner disk, i.e. from within the solar Galactocentric radius, by the effect of radial mixing (Sellwood & Binney, 2002). Given a Galactic radial metallicity gradient of 0.07–0.1 dex kpc^{-1} (e.g. Edvardsson et al. 1993; Wielen et al. 1996 and references; Maciel & Costa 2009), stars with a mean metallicity [Fe/H] = +0.35 will have originated at about 3–5 kpc from the Sun in the direction of the Galactic centre. If 25% of stars at this location systematically host giant planets, independent of metallicity, then the observed correlation between occurrence and metallicity follows from dilution introduced by radial mixing.

The origin of the Sun is not inconsistent with this picture. Wielen et al. (1996) inferred its birthplace at a Galactocentric radius of $R_{i,\odot} = 6.6 \pm 0.9$ kpc, based on its metallicity which is larger by 0.17 ± 0.04 dex than the av-

Thin and thick disk populations: While dominated by thin disk stars, the local stellar population contains approximately 5–10% of thick disk stars, and some 0.1–0.5% of halo stars. Any studies of the local disk population are therefore intimately connected with the determination and segregation of the ages, chemical composition, and velocity structures of the various component populations. Significant sub-structure in the local disk is also present in the form of open clusters, moving groups, and associations, including the Gould Belt.

The recognition of the existence of stellar populations differing in age, chemical composition, spatial distribution, and kinematic properties, represented a breakthrough in the knowledge of Galactic structure, and underpins the basis for recent models of galaxy formation and evolution. An extensive and complex literature now exists on the topic of the Galaxy's disk: its separation into thin and thick disk components, whether they represent discrete or continuous populations, their respective scale heights, their kinematic, metallicity, and age properties, the relationship between them, and their origin.

The vertical distribution of the different populations is frequently described either in terms of a *characteristic thickness*, defined as the ratio of the surface density (integrated over disk thickness) to its volume density at the Galactic plane, or in terms of a *scale height*, z_h, defined by $\exp(-z/z_h)$ for an exponential distribution. The thin and thick disks have characteristic thicknesses of 180–200 pc and 700–1000 pc respectively, with the interstellar medium having a scale height of about 40 pc (Dehnen & Binney, 1998). Even for the thin disk, however, its scale height is different for different classes of stars, with old stars found at greater distances from the plane partly as a result of disk heating in which the irregular gravitational field of spiral arms and molecular clouds gradually increases their random velocities over time.

Characteristic Galactic rotational velocities and velocity dispersions are of order $\langle V_{\rm rot}\rangle = 205, 180 \pm 50, 20$ and $\sigma_{uvw} = 20, 50, 100$ for the thin, thick and halo components respectively (Reid, 1998), where the velocity components uvw are taken conventionally towards the Galactic centre, in the direction of Galactic rotation, and towards the north Galactic pole, respectively. Numerous determinations can be found in the literature (e.g. Soubiran et al., 2003; Bensby et al., 2004).

erage of nearby stars of solar age, combined with a similar radial Galactic metallicity gradient. This is also consistent with its space motion, and has similar implications for the origin of nearby high-metallicity stars (Figure 8.13).

Haywood (2009) has suggested that planet formation is related, not to metallicity, but to the presence of molecular hydrogen in the form of the Galaxy's molecular ring (Clemens et al., 1988; Jackson et al., 2006). This provides a large reservoir of H_2, itself considered to be directly linked to star formation (e.g. Kennicutt, 2008). At its maximum density of 2–5 times its local density, 3–5 kpc from the Sun, planets are then expected to form preferentially. In this picture, the region of enhanced giant planet formation 'happens' to correspond to the

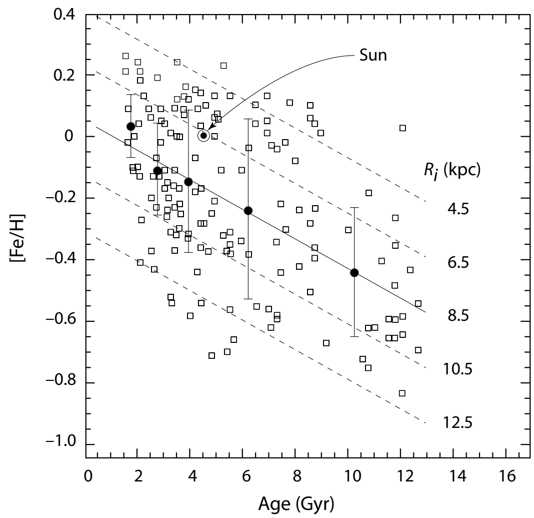

Figure 8.13: Places of formation of stars which are now nearby. Metallicity [Fe/H] is plotted against age for stars from the sample of Edvardsson et al. (1993). The position of the Sun is indicated. Inclined lines are of constant Galactocentric distance for their derived age–metallicity relation, such that the place of formation, R_i, can be determined for each star, including the Sun. Mean metallicities as a function of age are shown as filled circles. From Wielen et al. (1996, Figure 3), reproduced with permission © ESO.

metallicity range of 0.3–0.5 dex. Combined with radial mixing, this model offers consistency with the proportion of giant planets found around metal-rich and solar-metallicity stars (Figure 8.12).

In this picture, the giant star giant-planet hosts contain only a limited bias towards metal-rich objects because they are typically younger than the dwarfs, with ages of < 1 Gyr (Takeda et al., 2008b). Their relative youth implies that they are therefore less contaminated in metallicity by radial mixing.

The hypothesis has a further observational consequence: stars hosting non-giant planets, i.e. of Neptune or Earth mass, may form in less dense H_2 environments, such that a predominance of metal-rich stars among the Neptune/super-Earth hosts is not expected. Such behaviour has been confirmed in the HARPS results noted previously (Sousa et al., 2008).

8.4.4 Refractory and volatile elements

Planet formation involves *condensation*, the change from gaseous phase into the liquid or solid phase of the same element or chemical species. This involves the loss of kinetic energy by collision, or by adsorption onto an existing, colder, condensation centre.

In planetary science, elements and compounds with high equilibrium condensation temperatures are re-