

## ON THE CORRELATION BETWEEN METALLICITY AND THE PRESENCE OF GIANT PLANETS

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### ABSTRACT

The correlation between stellar metallicity and the presence of giant planets is well established. It has been tentatively explained by the possible increase of planet-formation probability in stellar disks with enhanced amount of metals. However, there are two caveats to this explanation. First, giant stars with planets do not show a metallicity distribution skewed toward metal-rich objects, as found for dwarfs. Second, the correlation with metallicity is not valid at intermediate metallicities, for which it can be shown that giant planets are preferentially found orbiting thick disk stars. Neither of these two peculiarities is explained by the proposed scenarios of giant planet formation. We contend that they are galactic in nature, and probably not linked to the formation process of giant planets. It is suggested that the same dynamical effect, namely the migration of stars in the galactic disk, is at the origin of both features, with the important consequence that most metal-rich stars hosting giant planets originate from the inner disk, a property that has been largely neglected until now. We illustrate that a planet–metallicity correlation similar to the observed one is easily obtained if stars from the inner disk have a higher percentage of giant planets than stars born at the solar radius, with no specific dependence on metallicity. We propose that the density of  $H_2$  in the inner galactic disk (the molecular ring) could play a role in setting the high percentage of giant planets that originate from this region.

*Key words:* Galaxy: disk – planetary systems – stars: abundances

### 1. INTRODUCTION

Metal-rich stars ( $[Fe/H] > +0.25$  dex) found in the solar neighborhood, including giant planet hosts, are objects that have migrated from the inner disk (i.e., inside the solar galactocentric radius) by the effect of radial mixing (Sellwood & Binney 2002; Haywood 2008b). This is an intriguing fact, but since it has been proposed that the prevalence of Jovian planets on metal-rich stars could be due to the enhanced probability of forming planetesimals in an environment enriched in metals, why should one bother about the galactic origin of the host stars? The first reason is that the correlation between stellar metallicities and the presence of giant planets is made up of stars of different galactic origins, which could bear some importance on the formation of giant planets themselves. The second is that the study of the effect of radial mixing permits new insights on two particularities that otherwise do not fit well into the scenario of metal-enhanced planet formation, namely the “normal” metallicity distribution of giant stars with planets (Pasquini et al. 2007; Takeda et al. 2008), and the fact that, at intermediate metallicities, giant planets seem to favor thick disk stars rather than thin disk objects (Haywood 2008a).

Both arguments are the subject of this Letter, which is laid out as follows: in Section 2, we briefly discuss the evidences of radial mixing and show how metallicity depends on the galactic orbital parameters of planet host stars. In Section 3, we show (1) the difference in the metallicity distribution of planet host giants and dwarfs and (2) the difference in the number of planet hosts between the thin and thick disks can be both explained as a consequence of radial mixing. In Section 4, we discuss the implication of these results, and demonstrate that if the percentage of giant planets among stars is dependent upon the galactocentric distance, a correlation between stellar metallicity, and the presence of a planet is a natural outcome of radial migration. Finally, we discuss what galactic property, dependent on galactocentric distance, could explain these new results.

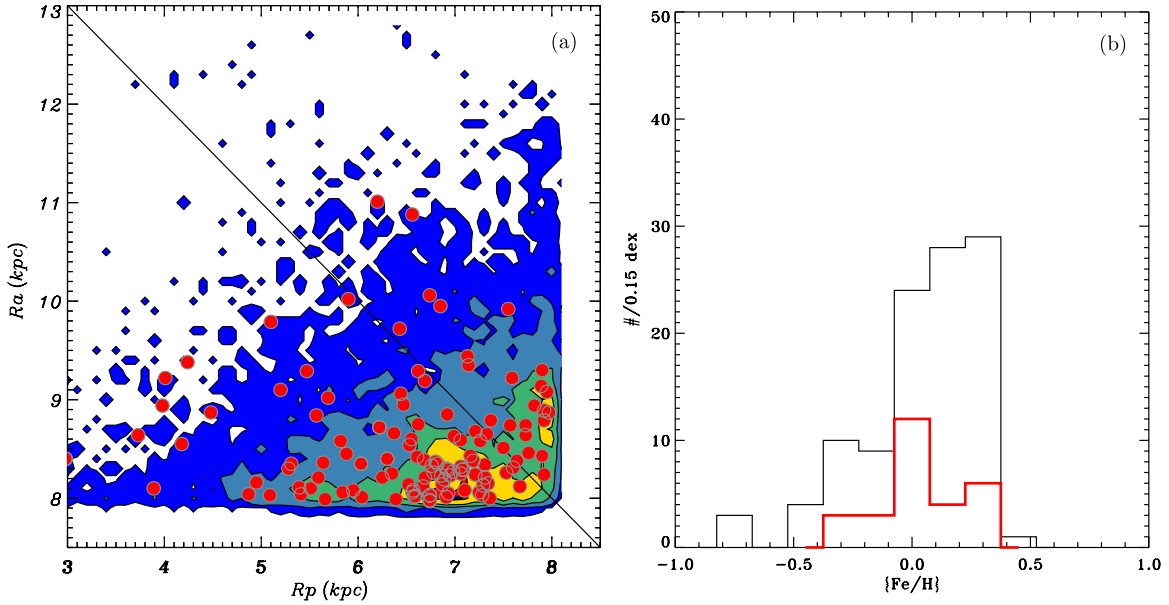
### 2. RADIAL MIXING IN THE GALACTIC DISK

#### 2.1. Evidences of Radial Mixing

The suggestion that stars migrate in the galactic disk has been around since at least the 1970s. A few dynamical processes have been claimed responsible for this phenomenon: random scattering (Wielen 1977), “churning” by spirals (Sellwood & Binney 2002) or perturbations by an orbiting satellite (Quillen et al. 2009), but specific observational evidence for any such processes remain elusive. The only direct evidence so far that such processes may be active is the differentiation encrypted in the orbital parameters of solar neighborhood stars considered as a function of metallicity. An example is given in Figure 4 of Haywood (2008b), which shows the clear difference in the distribution of apo- and pericenters for metal-poor and metal-rich stars. Other indirect evidence exists. One is the increasing metallicity dispersion with age (Haywood 2006, 2008b), which testifies that the older the star, the greater the distance over which it may have migrated, and therefore come from a region with significantly different mean stellar abundance. The second is that the “terminal” metallicity reached by the local chemical evolution is about 0.2 dex, not 0.4 or 0.6 dex. This is evidenced by the fact that there are no young stars above  $[Fe/H] \approx 0.2$  dex in the solar neighborhood. The solar radius has simply not reached this state of chemical evolution, and super metal-rich objects must have formed elsewhere, the inner disk being the most probable site.

#### 2.2. The Impact on the Planet Host Star Population

The galactic aspects of the bias toward metal-rich stars among planet hosts have been seldom investigated. In particular, the evidence that metal-rich stars of the solar vicinity must have come from the inner disk has been barely discussed. The exceptions are Ecuivillon et al. (2007) and Haywood (2008a). Several studies investigated whether planet host stars have properties that could differ from those of common field stars, but it has been so far rather unfruitful (see Udry & Santos 2007).



**Figure 1.** On the left, a density plot of the apocenter vs. pericenter of stars in the GCS catalog. The diagonal line represents a mean orbital radius of 8 kpc. Stars with planets and orbital parameters in the GCS catalog are plotted as large dots. On the right, the histograms of host planet stars that have  $R_{\text{mean}} = (R_p + R_a)/2 < 8$  kpc (thin line) or  $R_{\text{mean}} > 8$  kpc (thick red line).

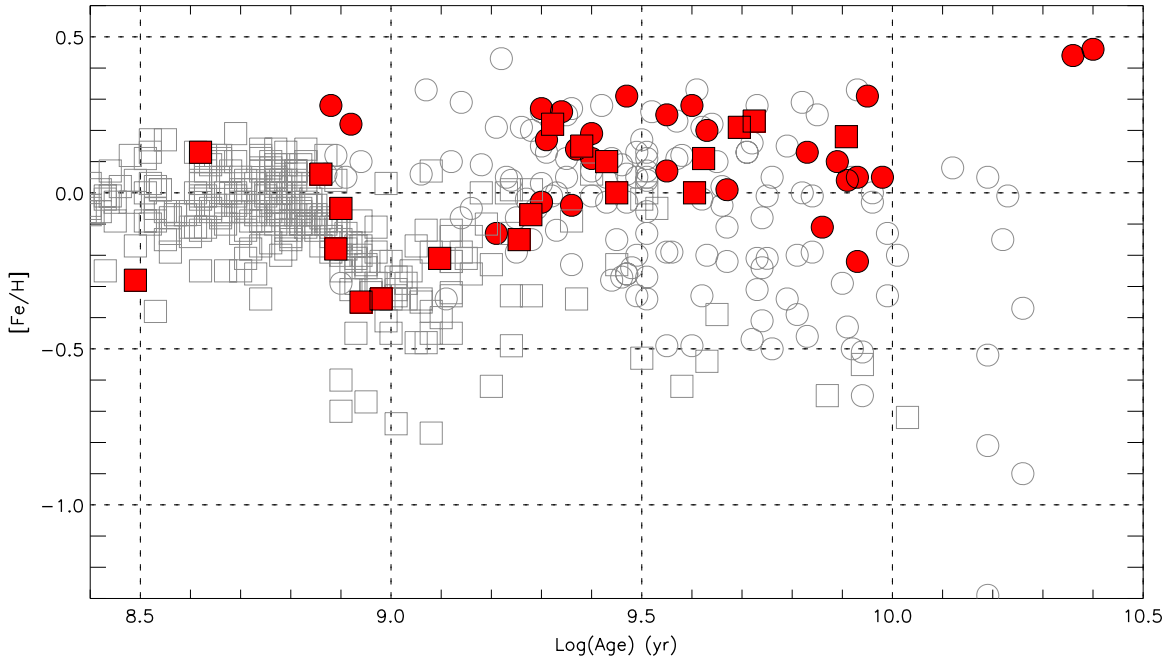
Robinson et al. (2006) found host stars to be overabundant in Si and Ni, but this has not been confirmed so far (see Gonzalez & Laws 2007). The only clear evidence of a difference has been reported in Haywood (2008a), where it was shown that at intermediate metallicities ( $[Fe/H] < -0.3$ ) most stars known to harbor giant planets belong to the thick disk rather than to the thin disk (in the ratio 10/2). We come back to this point in the following section. In any case, there is no reason to suspect that the metal-rich host stars are not being affected by radial mixing and that their origin would be different from other stars of the same metallicities.

Is there direct evidence of radial mixing among planet host stars? Figure 1(a) shows the pericenter–apocenter distribution for stars in the GCS (Geneva–Copenhagen Survey) catalog (Nordström et al. 2004) as a density–surface plot. The analysis of metallicity distribution of the stars in this plot shows that metal-poor thin disk populates preferentially the upper right part of the diagram ( $R_{\text{mean}} > 8$  kpc), or outer orbits, while the metal-rich stars occupy mainly inner orbits (see Haywood 2008b, Figure 6). This is interpreted as an effect of radial mixing. The metal-poor stars show a specific kinematic signature, having a component in the direction of rotation significantly larger than the local standard of rest (Haywood 2008b). A similar signature has been obtained by Schoenrich & Binney (2008) in modeling the effect of “churning,” which basically allows stars to swap between circular orbits of different angular momentum. Their Figure 3 shows that within a few Gyr, the mean orbital radius of a star can change by several kpc, both inward or outward. So we do expect that stars coming from inside the solar circle (respectively outside) to populate inner (outer) orbits. More details on the observational signatures and other consequences are given in Haywood (2008b). Sellwood & Binney (2002) describe the effect of “churning,” while Schoenrich & Binney (2008) discuss the chemical evolution aspects. Red symbols in Figure 1(a) represent known host-planet stars for which orbital parameters from the GCS catalog are available. The asymmetry in the distribution of orbital parameters is clearly apparent in

the stars with detected planets, with the overwhelming number of objects (79%) having  $R_{\text{mean}} = (R_p + R_a)/2 < 8$  kpc. The histograms on the right illustrate the metallicity distribution for the two groups of stars. It clearly shows that stars with planets are subject to a differentiation, the group with  $R_{\text{mean}} < 8$  kpc having a metallicity distribution similar to dwarfs hosting planets in general, while the group at  $R_{\text{mean}} > 8$  kpc has a metallicity centered on  $[Fe/H] = 0$ . It shows that planet hosts follow the general behavior of the metal-rich population and that the specific high metallicities can reasonably be attributed to a common origin in the inner disk.

### 3. TWO PITFALLS

After the discovery that the presence of Jovian planets is more frequent around metal-rich stars, several studies have explored how the formation of giant planets could be favored in a circumstellar disk enhanced in metals (Ida & Lin 2004; Mordasini et al. 2008). The results of the previous section now leads to the following preliminary question: how do we know that the higher percentage of giant planets detected on metal-rich stars is due to their metallicity and not to some other factor also linked with their origin in the inner disk? The question is relevant, because any measurable property of inner disk stars other than metallicity would be correlated with the presence of planet. The obvious a priori response is that metallicity is a measurable parameter, and intrinsic to the star. But there could be others however, which, although not measurable on the stars, could be no less important, such as, for example, the surface density of molecular hydrogen in the inner galactic disk regions. We now show that there are two cases where the planet–metallicity correlation is not verified, for which radial mixing provides a simple explanation, suggesting that metallicity may not be the relevant parameter. We will show in the following section that a bona fide planet–metallicity correlation can be obtained in the context of radial mixing with no metallicity dependence of any kind.



**Figure 2.** Age–metallicity relation for giants (squares) and dwarfs (circles) from Takeda (2007) and Takeda et al. (2008), complemented by “massive” ( $M > 1.4 M_{\odot}$ ) objects from the exoplanet database. Host planet dwarfs are shown as red large dots, and host planet giants as red filled squares. The mean metallicity of 14 planet host stars with ages  $< 2$  Gyr is  $-0.04$  dex.

### 3.1. The Difference in Giant–Dwarf Metallicity Distributions

The first case where the planet–metallicity correlation breaks down is the metallicity distribution of giant host stars. While the planet–host dwarf metallicity distribution is known to be skewed toward metal-rich objects, giant hosts are known to have a metallicity which is more like the field stars distribution; see, in particular, Takeda et al. (2008) and Pasquini et al. (2007).

Figure 2 shows the age–metallicity relation for field dwarfs and giants as derived by Takeda (2007) and Takeda et al. (2008). The progressive enlargement of the metallicity with age is well in accord with the effect of radial mixing, as noted in Haywood (2006, 2008b). The metallicity dispersion is smaller for giants: this is expected given their age distribution, Figure 2 shows that most giants have ages smaller than 1 Gyr. Since radial mixing is a secular process, its effect increases with time: the contamination by stars from the inner and outer disk is proportional to age. Because the sample of giants contains mostly young stars, it is little polluted by old, metal-rich, wanderers of the inner disk. The squares in Figure 2 show the planet host giant stars from Takeda et al. (2008), completed with the few other “massive” ( $M > 1.4 M_{\odot}$ ) objects available from the exoplanet database.<sup>1</sup> The figure illustrates that these objects, when older than about 2 Gyr, are mostly metal-rich ( $[Fe/H] > 0.0$  dex), while the 14 stars younger than 2 Gyr have a mean metallicity of  $-0.04$  dex. In the sample of Takeda et al., seven host giants (out of 10) are younger than 1 Gyr, and all are younger than 3 Gyr. The explanation for the difference between the dwarf and giant distributions comes out as a natural galactic effect: the giant sample contains a limited bias toward metal-rich objects because it is much younger than the dwarf sample, and then much less contaminated by radial mixing.

Pasquini et al. (2007) have suggested that the mass of the convective envelope could play a role. If the excess of metals

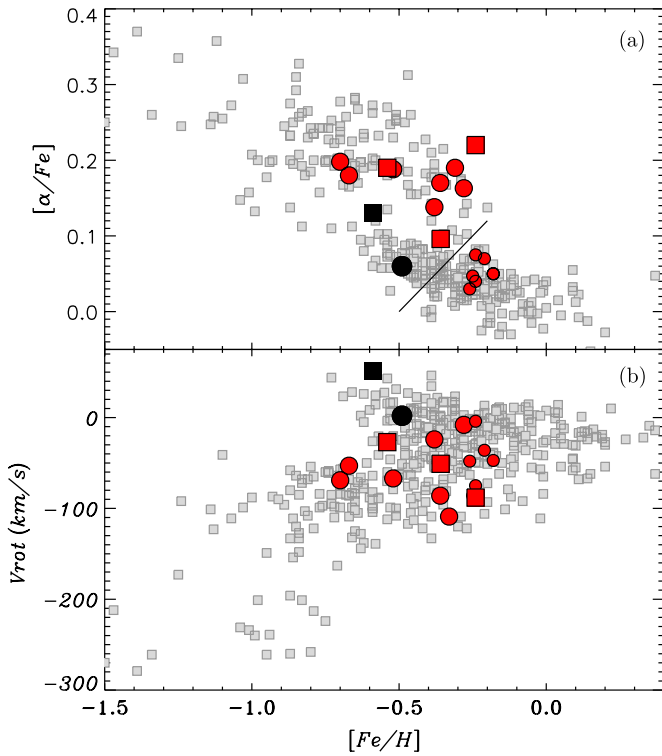
is due to pollution at the surface of stars, it could be diluted when the dwarf becomes a giant. We propose instead that the excess of metals is intrinsic to the star, and that the age is the determining factor, producing a selective effect on the origin of the stars.

### 3.2. The Difference between the Thin and Thick Disks

At intermediate metallicities ( $-0.7 < [Fe/H] < -0.3$  dex), stellar populations in the solar vicinity can be divided into two groups: the thin and the thick disks, which differentiate both by their  $\alpha$ -elements content and their asymmetric drift. At these metallicities, the thin disk is solar in  $\alpha$ -elements, but rotates faster than the LSR, while the thick disk is enriched in  $\alpha$ -elements ( $[\alpha/Fe] > 0.1$  dex) but lags the LSR. While the local metal-rich stars may be attributed to migration from the inner disk, the metal-poor end can be attributed to stars that came from the outer disk (see Haywood 2008b). It has been shown in Haywood (2008a) that in this metallicity interval, giant planets are found preferentially on thick disk stars. This is illustrated in Figure 3, where 10 stars with giant planets are compatible with being either thick disk or transition objects between the thin and the thick disks. Only one dwarf, HD 171028, and one giant, HD 170693, are compatible with being a member of the metal-poor thin disk with an origin in the outer disk. As commented in Haywood (2008a), this is significant, because the number of thin disk objects at these metallicities is expected to be higher or equal to the number of thick disk stars.

In Figure 3(a), six objects having  $[Fe/H] < -0.2$  dex are thin disk objects (smaller symbols below the line on plot (a)). The rotation lag and  $\alpha$ -element content of these stars (plot b) support the view that they are bona fide solar radius objects, with no specific indication that they would come from the outer disk. The search of new giant planet hosts in this metallicity range with no bias in favor or against either the thin disk and the thick disk is highly desirable to confirm this trend, but we think the difference between the two groups is significant.

<sup>1</sup> J. Schneider, <http://exoplanet.eu>



**Figure 3.** (a) Stars with giant planets at  $[\text{Fe}/\text{H}] < -0.2$  dex for which  $\alpha$ -element abundance is available (the mean of Mg, Si, Ca, Ti, or the last three for some giants). Gray squares are field dwarfs from Reddy et al. (2003, 2006) and Bensby et al. (2005). Large red dots or square symbols are host planet dwarfs or giants in the thick disk regime and transition zone between the thick and thin disks. The black dot and square represent the only dwarf (HD 171028) and giant hosting Jupiters clearly in the metal-poor thin disk regime ( $[\text{Fe}/\text{H}] = -0.49, -0.59$  dex) and  $V_{\text{rot}} = (+2, 51.5) \text{ km s}^{-1}$ . The smaller dots below the line are dwarfs clearly in the thin disk regime, with their lag in  $V_{\text{rot}}$  suggesting they are not from the outer disk. Plot (b) shows the velocity component in the direction of rotation as a function of metallicity for stars in plot (a). The field stars that make up the branch toward  $V_{\text{rot}} > 0$  and low metallicities ( $[\text{Fe}/\text{H}] < -0.3$  dex) are the metal-poor objects with a probable origin in the outer disk (at  $[\text{Fe}/\text{H}] < -0.3$  dex and  $[\alpha/\text{Fe}] < 0.1$  dex in plot (a)).

Finally, it should be noted that the galactocentric radii of origin of thick disk stars (those with  $[\text{Fe}/\text{H}] < -0.2$  dex and  $[\alpha/\text{Fe}] > 0.15$  dex in Figure 3) is not clear. According to Schoenrich & Binney (2008), we should expect the most metal-rich (at  $[\text{Fe}/\text{H}] > -0.4, -0.5$  dex) and  $\alpha$ -elements enhanced thick disk objects to come from the inner disk. This could be the case in particular for HIP 3497, HIP 26381, HIP 58952, HIP 62534, which all have metallicities above  $[\text{Fe}/\text{H}] = -0.5$ , and relatively high level of  $\alpha$  abundance. This is an interesting possibility since in this eventuality even thick disk objects could originate from the inner disk.

If metallicity was the determining factor for the presence of giant planet, we should not expect a difference between the number of planet host stars of the thin and thick disks. Since the metal-poor thin disks objects are expected to come from the outer disk, it is again suggested that the distance to the galactic center plays a role.

#### 4. DISCUSSION

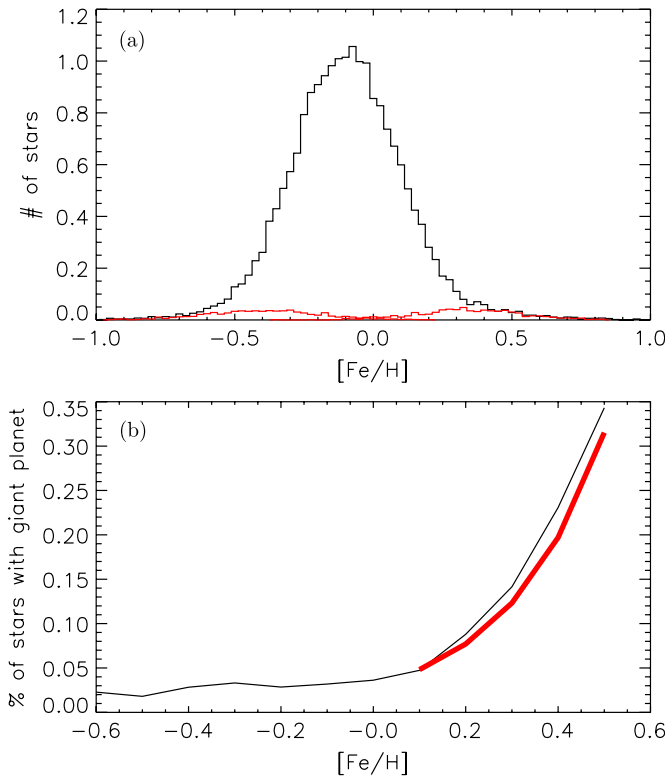
We are now facing the following picture: stars that come from the inner disk are noticeably rich in giant planets, while stars that come from the outer disk seems to be less favored in this respect. This new information changes considerably

how we envisage the correlation between metallicity and the presence of giant planets. For the surprising point here is not the fact that most host-planet stars are metal-rich, since they come from a region where most stars are metal-rich, but the very fact that most would come from the inner disk. We are led to conclude that the distance to the galactic center must somehow play a role in setting the percentage of giant planets, with two new questions: (1) what of the correlation between stellar metallicity and planet, and (2) what is the parameter linked to the galactocentric distance which could influence the percentage of giant planets?

(1) In this new scheme, the well-admitted correlation between metals and the presence of giant planets could be the mere reflection of the galactic origin of the stars, but does not necessarily imply an effect of the metallicity on the formation of giant planets. To illustrate this prediction, we make the following simple estimate. We adopt a “local” (e.g., for stars born at the solar galactocentric radius) Gaussian metallicity distribution centered on  $[\text{Fe}/\text{H}] = -0.1$  dex, with intrinsic dispersion 0.1 dex. We assume that about 4% (Grenon 1989) of the stars at the solar radius come from the inner disk, sampling a metallicity distribution centered on  $[\text{Fe}/\text{H}] = +0.35$ , with dispersion  $+0.2$  dex (a higher dispersion takes into account, in a simplified way, the fact that stars come from different inner radii, and therefore from regions where the mean metallicity is not strictly 0.35 dex). Given a metallicity gradient of about  $0.07\text{--}0.1$  dex  $\text{kpc}^{-1}$ , which is about what is measured (Maciel & Costa 2008) a mean metallicity  $[\text{Fe}/\text{H}] = +0.35$  dex can be expected toward the galactic center at about 3–5 kpc from the Sun. We assume that the percentage of host-planet stars in the inner disk is 25% (as measured on the most metal-rich objects of the solar neighborhood) and independent of metallicity. We also assume a 4% of metal-poor stars centered on  $[\text{Fe}/\text{H}] = -0.4$  dex, with a dispersion in metallicity of  $+0.2$  dex, with no giant planets. Finally, an error on measured metallicities is simulated with a random Gaussian with 0.15 dex dispersion. The metallicity distribution generated with these parameters is given in Figure 4(a). In plot (b), we show the proportion of stars with giant planets obtained with our assumptions. The thick line is the fit made by Udry & Santos (2007) on the observational distributions ( $3.01 \times 10^{2.04[\text{Fe}/\text{H}]}$ ). As can be seen, a good correlation between the presence of a giant planet and the metallicity of the stars is obtained, providing an honest fit to the observed rate.

(2) Some factor linked to galactocentric distance, but not metallicity, must play a role in setting the percentage of giant planet. A candidate could be the density of dust in the inner disk, because dust is thought to favor the formation of planetesimals. However, there is, as yet, no evidence for a difference between the distributions of dust and metals in our Galaxy, so that we do not expect dust to lead to different patterns than metallicity. A better candidate is molecular hydrogen. It is foremost a fundamental ingredient for the formation of giant planets, being the principal constituent of stellar disks and Jupiters. Its main structure in the Galaxy, the molecular ring, is thought to contain 70% of  $\text{H}_2$  gas inside the solar circle (Clemens et al. 1988; Jackson et al. 2006), thereby providing a huge reservoir for star ( $\text{H}_2$  is known to be directly linked to star formation (Kennicutt 2008)) and planet formation. The most interesting aspect, however, is the fact the molecular ring reaches a maximum density at 3–5 kpc from the sun, corresponding to the distance where stars with metallicity in the range  $(+0.3, +0.5)$  dex are expected to be formed preferentially. Interestingly, the mean





**Figure 4.** (a) Simulated “local” metallicity distribution. In red, the contributions of the metal-rich and metal-poor components assumed to have come to the solar neighborhood by radial migration. See Section 4 for details. (b) The percentage obtained assuming the metallicity distribution and intrinsic giant planet proportion of 0% in the metal-poor component, 5% locally, 25% in the metal-rich component. The thick line is the percentage of planet host vs. stellar metallicity according to the fit given by Udry & Santos (2007).

surface or volume density of  $H_2$  at a galactocentric distance of 4–5 kpc is two to five times its local value (Nakanishi & Sofue 2006), in proportion with the rate of giant planets on metal-rich (25%, roughly  $\pm 10\%$ ) and solar metallicity stars (4%).

A final indication may come to support our views. Stars hosting only Neptunian and/or super-Earth should be less prone to having an origin in the inner disk, if they can form in an environment less dense in  $H_2$ . Which means that we should not expect a predominance of metal-rich stars among Neptunian/super-Earth host stars. Among the 12 objects on which Neptunian or super-Earth planets have been discovered,

seven with no Jovian planets have metallicities  $-0.28$ ,  $-0.33$ ,  $-0.31$ ,  $-0.31$ ,  $-0.05$ ,  $-0.1$ , and  $-0.15$  (GJ 674, Gl 581, HD 4308, HD 40307, HD 69830, HD 285968, HD 7924) according to the exoplanet database. The five stars also harboring Jovian planets (HD 75732, Gl 876, HD 47186, HD 160691, HD 181433) have metallicities  $+0.29$ ,  $-0.12$ ,  $+0.23$ ,  $+0.28$ , and  $+0.33$  dex, amply confirming the possibility that the first group of stars could be genuine solar radius objects, and the second wanderers from inside the Galaxy.

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