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ARE STARS WITH PLANETS POLLUTED?

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ABSTRACT

We compare the metallicities of stars with radial velocity planets to the metallicity of a sample of field dwarfs. We confirm recent work indicating that the stars-with-planets sample as a whole is iron-rich. However, the lowest mass stars tend to be iron-poor, with several having [Fe/H] < -0.2, demonstrating that high metallicity is not required for the formation of short-period Jupiter-mass planets. We show that the average [Fe/H] increases with increasing stellar mass (for masses below 1.2 $M_\odot$) in both samples, but that the increase is much more rapid in the stars-with-planets sample. The variation of metallicity with stellar age also differs between the two samples. We examine possible selection effects related to variations in the sensitivity of radial velocity surveys with stellar mass, apparent magnitude, and stellar metallicity, and identify a color cutoff ($B-V \gtrsim 0.48$) that contributes to but does not explain the mass-metallicity trend in the stars-with-planets sample. We use Monte Carlo models to show that adding an average of $\sim 5\ M_\oplus$ of iron to each star can explain both the mass-metallicity and the age-metallicity relations of the stars-with-planets sample. However, for at least one star, HD 38529, there is good evidence that the bulk metallicity is high. We conclude that the observed metallicities and metallicity trends are likely the result of the interaction of three effects: accretion of $\sim 5\ M_\oplus$ of iron-rich material, selection effects, and high intrinsic metallicity.

Subject headings: planetary systems — stars: abundances — stars: chemically peculiar

1. INTRODUCTION

Radial velocity surveys have established that $\sim 7\%$ of solar-type stars in the solar neighborhood have periodic velocity variations with semiamplitude $K \gtrsim 10$ m s^{-1} (Marcy, Cochran, & Mayor 2000). The interpretation of these velocity variations as being due to the presence of Jupiter-mass planets was clinched by the observations of transits in HD 209458 (Charbonneau et al. 2000; Henry et al. 2000). The surveys have revealed three surprising properties: first, many of the systems have planets in extremely small (0.03–0.1 AU) orbits; second, the orbits, when not subject to tidal damping, are often highly eccentric ($e \sim 0.3$ being typical); finally, the host stars are often highly metal rich (Gonzalez 1997).

In this paper we explore possible explanations for the high metallicities of the stars with planets. Two general classes of explanation have been proposed for the high metallicities seen in stars with planets: high intrinsic metallicities and accretion of metal-rich material. A correlation between high intrinsic metallicity and the presence of a radial velocity planet might arise if metal-rich gas disks are a prerequisite of either planet formation or planet migration. Alternately, such a correlation could result from the ingestion of rocky material or metal-rich gas giant planets as a result of the migration process.

Here we point out that a third explanation is currently viable, namely, selection effects. We discuss several possible selection effects. We point out an apparent color cutoff in the underlying samples producing the radial velocity stars. We briefly discuss the effects of a possible apparent-magnitude limit. We also discuss the bias associated with the finite velocity precision of the surveys, combined with the apparent increase in number of planets with decreasing planetary mass.

In this paper we examine all three types of explanations by comparing the sample of radial velocity planet stars with a sample of dwarf stars in the solar neighborhood recently studied by Murray et al. (2001). We find that the available data are consistent with the notion that a substantial amount of iron, of the order of five Earth masses (5 $M_\oplus$) on average, has been accreted onto the central stars in the radial velocity systems. However, it is also possible that the trends in metallicity we see are due to the selection effects mentioned above. The explanation based on high intrinsic metallicity does not explain the variations in metallicity as a function of stellar mass that we find. However, there is evidence that *some* radial velocity systems are intrinsically metal-rich; HD 38529 sits in the Hertzsprung gap, indicating that it currently has a very deep convection zone, and yet it has a high metallicity.

The paper is organized as follows. In § 2 we examine the $B-V$ colors as a function of stellar mass, and the distribution of metallicity as a function of stellar mass and age for both stars with planets and the Murray et al. (2001) sample. We show that the radial velocity sample has $B-V > 0.48$, but in § 2.1 we argue that neither this nor the difficulty of achieving high-precision radial velocities for metal-poor or blue stars completely explains the metallicity trends we find. Neither does the decreasing sensitivity of radial velocity surveys with increasing stellar mass (with the subsequent weakening of the absorption lines), combined with the reduced frequency of more massive planets, appear to explain the sharp increase in [Fe/H] with increasing stellar mass. In § 3 we use Monte Carlo models of stellar pollution to estimate the amount of accreted iron needed to reproduce the observed metallicity trends,

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assuming that they are not due to selection effects. In § 4 we compare our results with recent work by other authors, and we summarize our conclusions in § 5.

2. STELLAR METALLICITY

We find the masses and ages of the known planet-bearing stars using their *Hipparcos* parallaxes, combined with their V magnitudes, their effective temperatures $T_{\rm eff}$, if available (or $B-V$ colors when $T_{\rm eff}$ is not known), and their metallicities [Fe/H]. For the bulk of the stars with planets we use spectroscopically determined values of the metallicity taken from the literature (Castro et al. 1997; Gonzalez & Vanture 1998; Gonzalez 1998; Gonzalez, Wallerstein, & Saar 1999; Gonzalez & Laws 2000; Fischer et al. 1999; Santos et al. 2000; Gonzalez et al. 2001), but in the case of a few of the more recently discovered systems, we use color-based metallicities, primarily from the CORAVEL Web site.[4] We fit to the grid of stellar models described in Murray et al. (2001), to which we refer the interested reader for further details.

In finding the ages and masses of the stars, we have used models that have uniform compositions. In light of the findings presented below, such models are only good as a lowest order approximation. We have modified Chaboyer's stellar evolution code to handle polluted models but defer discussion of the results to later publications.

We compare the sample of stars with planets to the sample of 466 main-sequence stars and to a sample of 19 slightly evolved (or "Hertzsprung gap") stars described in Murray et al. (2001). The color-magnitude diagram for both samples is shown in Figure 1. The Hertzsprung gap stars are located in the sparsely sampled region between the main sequence (running from the lower right to the upper left hand corner of the plot) and the giants (in the upper right hand corner); the gap stars are just coming off the main sequence and have convection zones 10 times more massive than the surface mixing layer the star possessed while on the main sequence (either convectively or rotationally mixed). They are useful as a control, since their deep convection zones tend to minimize the effect of any accretion of iron-rich material that may have occurred while the star was on the main sequence.

We note that there are two giants stars in the current sample of stars with planets. One of these, HD 177830, has a radius of about 10 $R_{\odot}$ according to our models. However, its planet orbits at 1.1 AU, still at many tens of stellar radii. Direct comparison between the metallicities of dwarfs and giants are problematic, so the giant stars are not shown in any of the following plots.

Figure 2 shows stellar mass as a function of the B-V color for both samples. The bottom panel is the data for the Murray et al. (2001) stars, the top panel for stars with planets; in both panels the filled squares represent stars on the main sequence, while the open triangles represent stars in the Hertzsprung gap. Comparing the two panels shows that the radial velocity surveys have a selection effect; with two exceptions, all the stars with planets have $B-V > 0.48$ (Fig. 2, *horizontal solid line*). In contrast, the Murray et al. stars less massive than 1.5 $M_{\odot}$ range down to $B-V \approx 0.3$.

At fixed stellar mass, metal-poor stars have lower values of $B-V$ than metal-rich stars of the same age. Alternately,

[4] CORAVEL Web site is available at: http://obswww.unige.ch/~udry/planet/planet.html.

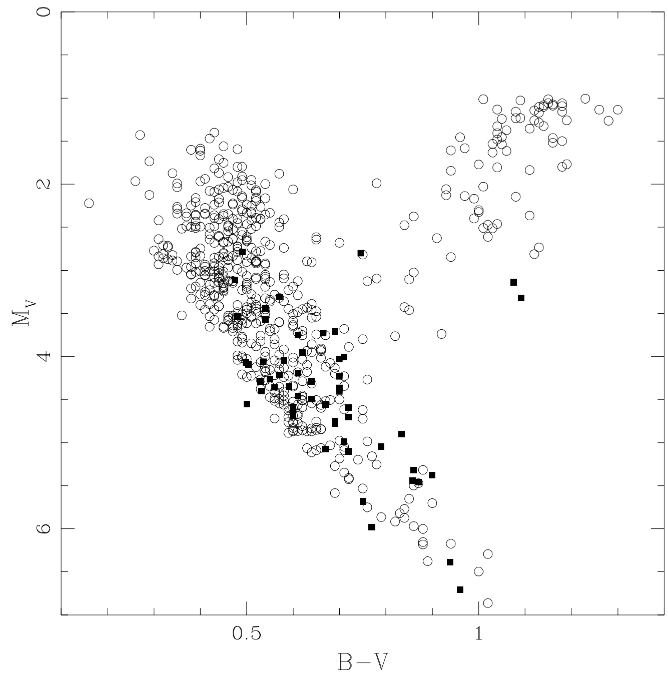

FIG. 1.—Color-magnitude diagram for both stars with planets (*filled squares*) and the Murray et al. (2001) sample (*open circles*). The Hertzsprung gap lies between the main sequence to the lower left and the giant branch at the upper right; only one star with planets lies in the gap, while 19 stars from the Murray et al. sample are located there.

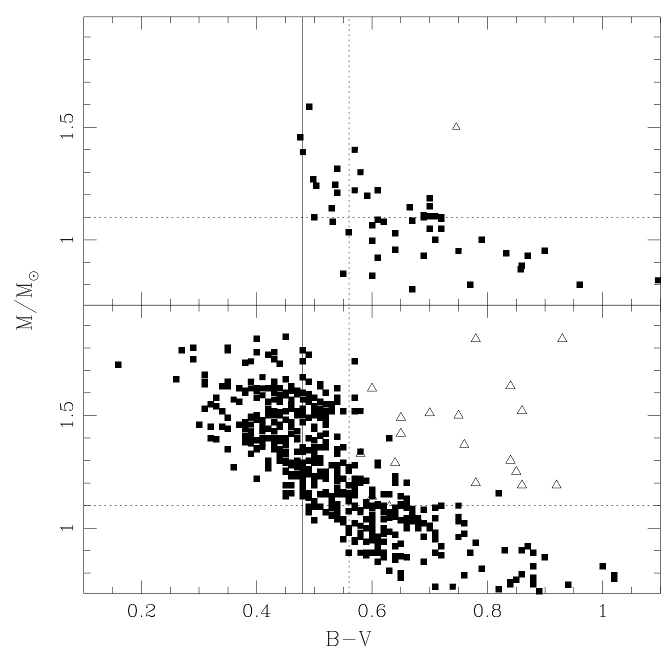

FIG. 2.—Stellar mass plotted as a function of stellar color $B-V$. The bottom panel shows the sample of Murray et al., consisting of 466 main-sequence stars (*filled squares*) and 19 slightly evolved "Hertzsprung gap" stars (*open triangles*). The top panel shows 49 main-sequence stars with planets (*filled squares*), and one slightly evolved star with planets (*open triangle*). The dotted horizontal line is at $M/M_{\odot} = 1.1$. The solid vertical line is at $B-V = 0.48$; we attribute the lack of stars with planets to the left of this line to an observational selection effect. This selection does not affect the stars-with-planets sample below 1.1 $M_{\odot}$. The dotted vertical line at $B-V = 0.56$ corresponds to the cutoff in the Santos et al. (2001) sample of stars with no radial velocity planets.

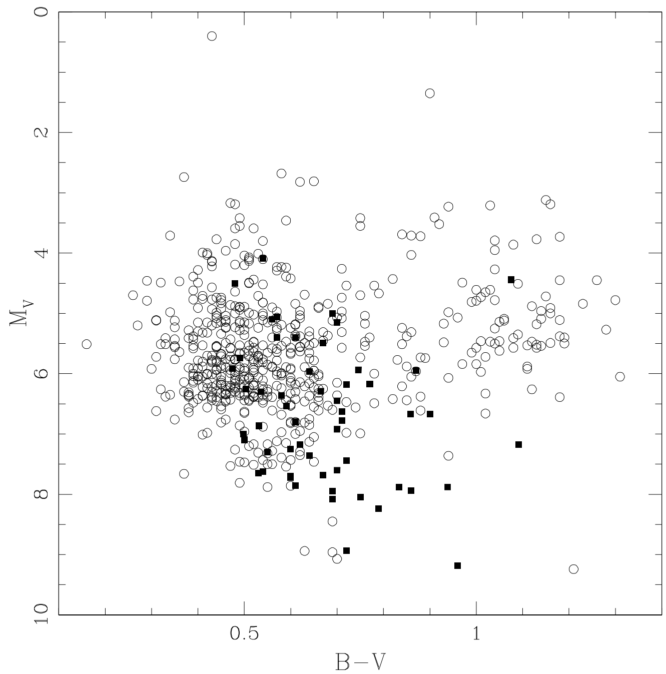

FIG. 3.—Apparent V magnitude plotted as a function of stellar color $B-V$. The stars-with-planets sample is better covered at $V \gtrsim 8$ than the Murray et al. sample.

at fixed $B-V$, increasing stellar mass implies increasing metallicity. Thus, the current radial velocity surveys are biased against high-mass, low-metallicity stars, and a plot of [Fe/H] versus mass based on such a selection criterion will have a lower limit corresponding to increasing [Fe/H] with increasing mass.[5]

We note, however, that for stars less massive than ~ 1.1 $M_\odot$, none of the stars in the Murray et al. sample have $B-V < 0.48$; so for stars less massive than this, the color cutoff introduces no bias. Furthermore, we show below that applying the $B-V$ cutoff to the Murray et al. sample introduces only a slight change in an [Fe/H] versus mass plot, a change not large enough to explain the difference between the Murray et al. sample and the sample of stars with planets.

The current radial velocity surveys are magnitude limited as well as color limited. At fixed mass, higher metallicity stars are less luminous, and hence tend to have larger V magnitudes. Thus, the surveys are biased against low-mass, high-metallicity stars (G. Laughlin 2001, private communication; N. C. Santos 2001, private communication). A plot of [Fe/H] versus mass subject to such a selection will have an upper limit corresponding to increasing [Fe/H] with increasing mass, showing the same trend as the $B-V$ selection mentioned above, but for large rather than for small $B-V$.

Figure 3 shows V versus $B-V$ for both samples. We note that the Murray et al. sample has a more severe V cutoff than the planet sample; hence, the Murray et al. sample is likely to be biased against low-mass, high-metallicity stars simply because they are not represented. This could introduce a trend of increasing [Fe/H] with increasing mass in the Murray et al. sample. However, we show below that the stars-with-planets sample shows an even steeper increase of [Fe/H] with stellar mass than the Murray et al. (2001) sample, a finding that is difficult to explain as the result of a V cutoff in the stars-with-planets sample.

Figure 4 shows the metallicity histograms of the Murray et al. sample and the stars with planets. The unshaded histogram drawn with the heavy solid line is for all the stars in the Murray et al. sample, while the histogram drawn with the dotted line includes only stars in that sample with $B-V > 0.48$; the difference is negligible. It is clear that the stars-with-planets sample is metal-rich relative to the other two samples, supporting the results of earlier workers (Santos et al. 2000; Laughlin 2000; Gonzalez et al. 2001). It is also clear that this difference is not due to the color selection criterion.

A histogram of those stars with planets having $M_* \leq 1.1$ $M_\odot$ has a lower average metallicity, but so does the analogous histogram for the Murray et al. sample; the result is that there is still a significant difference between the two samples. Since stars with $M_* \leq 1.1$ $M_\odot$ do not appear to be as blue as $B-V = 0.48$, this demonstrates again that the difference in [Fe/H] between the two samples is not due to the apparent $B-V$ selection.

The excess metallicity of the stars with planets is even more striking when the metallicity is plotted as a function of stellar mass, as in Figure 5 (see also Laughlin 2000). The bottom panel shows the metallicity of the stars from Murray et al. having $B-V > 0.48$. The top panel shows the metallicity of the stars with planets (excluding two giants). From this figure it is clear that while low-mass stars with planets cover the same range of metallicities as the Murray et al. sample, the high-mass stars with planets are all metal-rich.

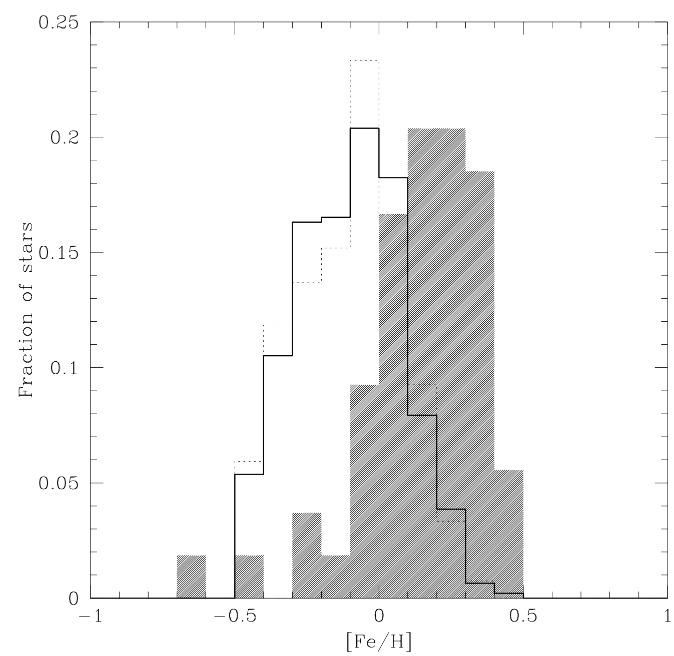

FIG. 4.—Metallicity distribution of stars with planets (*shaded histogram*) compared with the field dwarfs in the Murray et al. (2001) sample. The dotted histogram is the result of restricting the field dwarfs to have $B-V > 0.48$, as appears to be the case for the stars-with-planets sample (see Fig. 2).

[5] The cutoff in $B-V$ could be a real effect, as opposed to a selection effect. However, we note below that the sample from which the planet-bearing stars found by Mayor and coworkers were drawn appears to have $B-V > 0.56$.

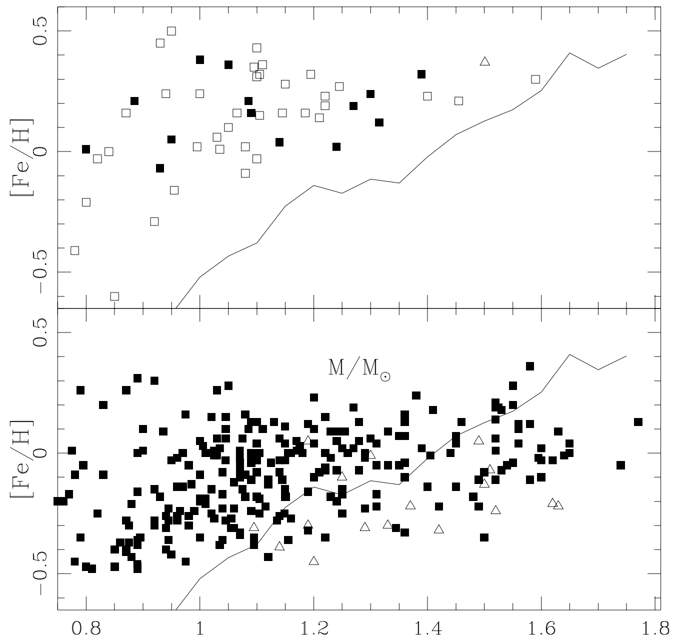

FIG. 5.—Stellar metallicity as a function of stellar mass, where the mass is obtained by fitting to our stellar models. The top panel is for stars with planets, the bottom for stars in the Murray et al. sample. Filled squares represent unevolved stars having planets with $a \leq 0.1$ AU, open squares unevolved stars having planets with $a > 0.1$ AU, while open triangles represent Hertzsprung gap stars. The solid line in both panels corresponds to the mass and metallicity of main-sequence stars with $B-V = 0.48$, calculated at the age at which $B-V$ is minimized. Stars below and to the right of this line can have $B-V > 0.48$ if they are either very young or slightly evolved; hence, the overabundance of Hertzsprung gap stars in this region. The fact that the stars with planets lie well above this line suggests that their high metallicity is not simply due to the $B-V$ selection.

In the top panel of Figure 5 we have depicted those stars having planets with semimajor axes $a > 0.1$ AU by open squares. The filled squares denote those stars with "hot Jupiters," having $a \leq 0.1$ AU. In Figure 6*a* we show all stars having planets with $a > 0.5$ AU. It demonstrates that the metallicity trends seen in the stars-with-planets sample (Fig. 5) are not strong functions of the semimajor axis of the planets. We discuss the significance of this result in § 4.

The solid line in both panels of Figure 5 shows the boundary between Chaboyer's stellar models with $B-V > 0.48$ (up and to the left of the line) and those with $B-V < 0.48$ (below and to the right). The calculated values of $B-V$ depend on the age of the model; both pre–main-sequence and evolved stars are redder than stars of the same mass and metallicity on the main sequence. In plotting the solid line we have taken models on the main sequence at or near the age at which $B-V$ is minimized. If all the stars in both samples were near the zero-age main sequence, essentially all would be above and to the left of this solid line (assuming our colors are good matches to those of real stars). This is true for the stars-with-planets sample, but not for the Murray et al. sample. Our models indicate that the latter sample has many stars that are evolving off the main sequence and that are currently redder than $B-V = 0.48$, even though younger stars with their mass and metallicity would have $B-V < 0.48$. The location of the Hertzsprung gap stars (Fig. 6, *open triangles*) is consistent with this interpretation. The width of the main sequence in Figure 1 near the upper end ($M_V \approx 2$) is also consistent with this picture.

If the trend of increasing [Fe/H] with increasing mass were due to the (apparent) color selection of the radial velocity surveys, we would expect that the bulk of the metallicities of the parent stars would be above and to the left of this solid line, with the possibility that some slightly evolved stars would be below and to the right, as is seen in the Murray et al. sample. In fact, all the stars with planets *are* above the $B-V = 0.48$ line; even for stars with mass below 1.1 $M_\odot$, when the color selection should not matter (according to Fig. 2), the stars with planets are all well above the line. We conclude that the mass-metallicity trend seen at the high-mass end of the stars-with-planets sample is not due entirely to the $B-V$ cutoff; as noted above, in the

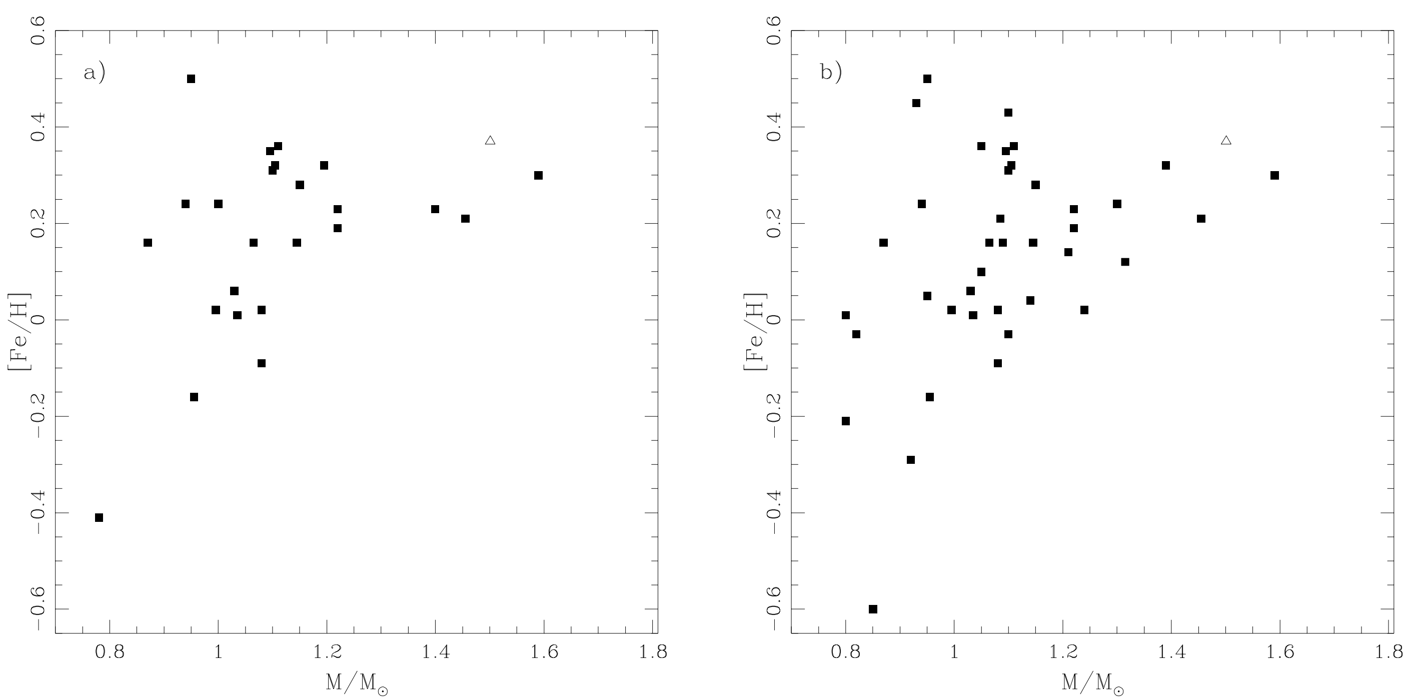

FIG. 6.—(*a*) Same as in the top panel of Fig. 5, but only for stars whose innermost planet has $a > 0.5$ AU. (*b*) The same, but for stars with $K > 50$ m s^{-1}.

case of stars with $M_* < 1.1\ M_\odot$, the color cutoff has no effect.

Binning the data by mass (Fig. 7) again shows that the metallicity properties of the Murray et al. sample differ from those of the stars with planets. The data points in this figure show the average [Fe/H] in mass bins 0.1 $M_\odot$ wide, along with the associated standard errors (variance divided by the square root of the number of star less one). The open squares correspond to the Murray et al. sample; the filled squares correspond to a subset of that sample with $B-V > 0.48$. As noted above, the color selection criterion does not effect the metallicity distribution for stars below $\sim 1.1\ M_\odot$; even for more massive stars, the differences between the average [Fe/H], with and without applying the color cutoff, while noticeable, are much smaller than the differences between the Murray et al. sample and the stars-with-planets sample (*filled triangles*).

We note that the average metallicity of the stars with planets rises much more rapidly with increasing mass than either the Hertzsprung gap or the main-sequence stars without planets. This strongly suggests that the stars with planets have accreted iron-rich material after they reached the main sequence. We quantify this below.

It is also instructive to plot metallicity as a function of stellar age, since younger stars are expected to be metal-rich when compared to older stars. As seen in the bottom panel of Figure 8, there is a correlation between stellar age and metallicity in the Murray et al. sample; younger stars are, on average, more metal rich than older stars. The average value of [Fe/H] rises steadily from ~ -0.2 at 10 Gyr to $\sim +0.05$ at the present. Compared to this rather regular rise, the age-metallicity distribution of the stars-with-planets sample (*top panel*) is odd. It jumps rather abruptly from ~ 0.0 (or solar) at ~ 10 Gyr to $+0.2$ for stars of all ages less than ~ 5 Gyr.

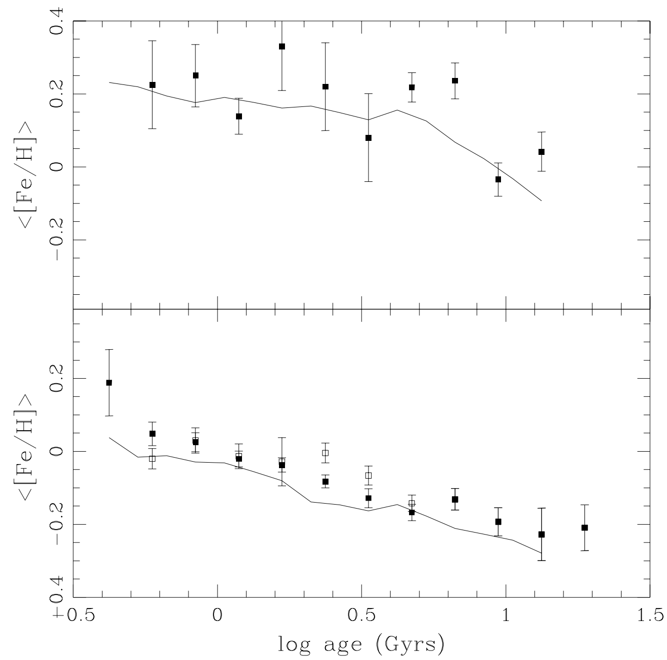

FIG. 8.—Average stellar metallicity in age bins of width Δ log (age) = 0.15. There are roughly 20 stars per bin for the Murray et al. sample (*bottom panel*), but only a few per bin for the stars-with-planets sample (*top panel*). Nevertheless, it is clear that the two distributions differ dramatically. The solid lines show the predicted average [Fe/H] values for polluted models; in the bottom panel the average accreted iron mass is 0.4 $M_\oplus$, while in the top panel it is 6.5 $M_\oplus$.

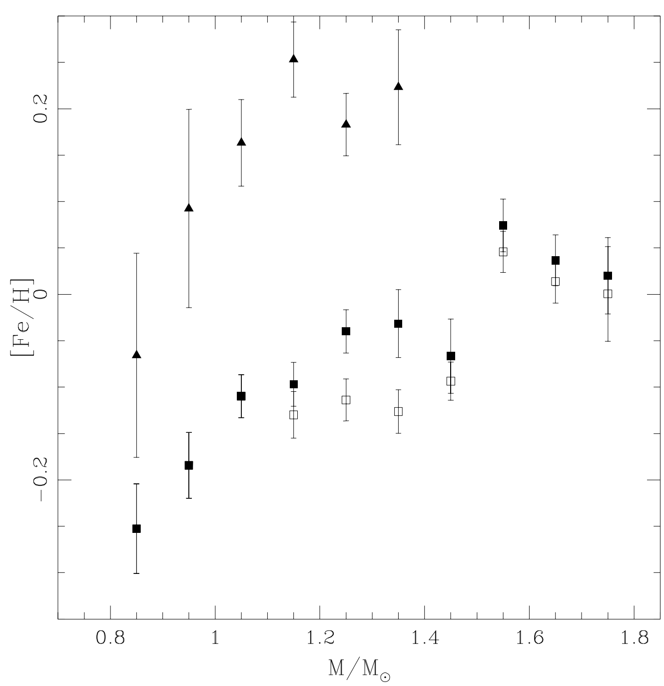

FIG. 7.—Stellar metallicity binned as a function of stellar mass. Open squares represent unevolved stars from the Murray et al. sample, while filled squares result from requiring $B-V > 0.48$. As expected, there is no difference between the open and filled squares below 1.1 $M_\odot$, so the open squares cannot be seen below that mass. The filled triangles represent the stars with planets. Note that even for stars with masses $\lesssim 1.1\ M_\odot$, where the color selection plays no role, the stars with planets have much higher metallicity than the stars in the Murray et al. sample, and that the metallicity increases rapidly with stellar mass (more rapidly than in the Murray et al. sample).

We must account for the difference in $B-V$ between the two samples to make a fair comparison; we do so by plotting only those stars with $B-V > 0.48$ and mass less than 1.45 $M_\odot$ as open squares in the bottom panel. There is a slight difference, but the result is nothing like the data in the top panel.

2.1. *Is the Rise of* [Fe/H] *with Mass a Selection Effect?*

The sample of stars with planets was apparently drawn from a stellar sample with a selection criterion of $B-V \gtrsim 0.48$. This by itself cannot explain the rapid rise of metallicity with stellar mass, as demonstrated by Figures 5 and 7.

However, there is another possible selection effect. The radial velocity technique relies on a cross-correlation between a known spectrum (usually provided by an iodine cell placed in the beam) and the stellar spectrum. Stars that are more massive, and hence hotter, have weaker lines than less massive stars; similarly, metal-poor stars have weaker lines than metal-rich stars. Thus, massive metal-poor stars will have weak, sparse spectra, and achieving high-precision radial velocities for such stars is likely to be problematic.

This line of argument suggests that part of the metallicity trend we see might be due to the inability of radial velocity surveys to identify planets around massive metal-poor stars. To evaluate this properly, one could examine the radial velocity errors as a function of stellar mass and metallicity or as a function of $B-V$, since increasing mass and decreas-

ing metallicity both tend to reduce $B-V$. We urge observers to do so.

Lacking this information, we instead examine the distribution of the semiamplitude K with stellar mass; see Figure 9. There does appear to be a mass-dependent lower envelope; for stars more massive than $\sim 1.1\ M_\odot$, the minimum K increases with increasing stellar mass. We also note that for stars less massive than the Sun, the minimum K increases with *decreasing* stellar mass. We believe that both of these trends are likely to be due simply to the small numbers involved; most stars with planets have very nearly solar masses, with only a few stars more massive than 1.2 $M_\odot$ or less massive than 0.85 $M_\odot$. However, it is possible that the apparent trends are due to a K selection effect. Here, we assume that it is and show that such a selection does not appear to explain the rapid rise in [Fe/H] with stellar mass.

To do so, we plot [Fe/H] versus stellar mass, but only for those systems having $K > 50$ m s^{-1} (see Fig. 6*b*), on the assumption that the current surveys are reasonably complete for K this large. The trend with stellar mass is unchanged.

There is a third possible selection effect related to the masses of the parent stars. The distribution of planet masses appears to indicate that there are more low-mass planets than high-mass planets. A power law provides a rough fit, $N(m) \sim m^{-\alpha}$, with α the of order of 1. Suppose that the current radial velocity surveys can detect $K = K_{\rm min}$ for all stars up to 1.6 $M_\odot$. A star of 1.6 $M_\odot$ must have a planet twice as massive as a star of 0.8 $M_\odot$ in order to produce a wobble of amplitude $K_{\rm min}$. The more massive star is then only $2^{-\alpha}$ as likely to have such a planet, assuming that stars of different masses have the same chance of having a planet of a fixed mass. Examining equal numbers of high- and low-mass stars would then yield more planets around low-mass stars. If the sample is not complete near $K_{\rm min}$, the high-mass stars would then tend to be more metal rich than the low-mass stars, since the low-metallicity high-mass stars with low K would be harder to detect. We believe, however, that the current samples are reasonably complete for $K > 50$ m s^{-1}, so this seems unlikely to explain the strong trend seen in the [Fe/H] versus stellar mass plot.

We tentatively conclude that the trend of increasing [Fe/H] with increasing stellar mass is a real physical effect. The odd distribution of [Fe/H] with stellar age for the stars-with-planets sample is also hard to explain as the result of a selection effect. Assuming that stars with planets only form in high-metallicity clouds also fails to explain the age-metallicity relation, since it would predict uniformly high metallicities. In the next section we present Monte Carlo models of polluted stellar populations and compare them to the data.

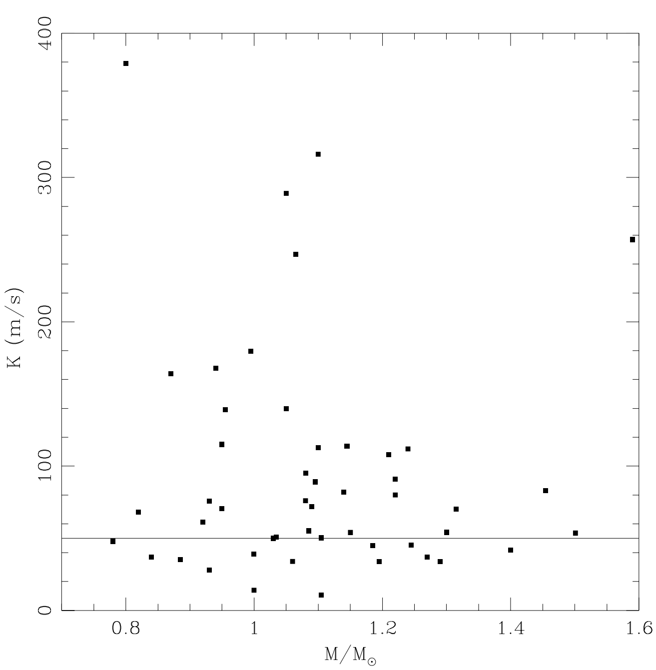

FIG. 9.—Amplitude K of the radial velocity plotted against stellar mass for the known extrasolar planets. There is a hint of a lower envelope for high-mass stars, running from 10 m s^{-1} at 1.1 $M_\oplus$ to $\sim$50 m s^{-1} at 1.5 $M_\oplus$. The current radial velocity surveys may well be able to detect planets around 1.5 $M_\odot$ stars at lower radial velocities, but we take 50 m s^{-1} as a conservative estimate for the radial velocity at which the surveys are complete in the mass range $0.8 \leq M/M_\odot \leq 1.5$. Note that there are several systems with $K > 400$ that are not shown in this plot. Note also that there is a hint of a selection against small K in stars less massive than 1 $M_\odot$. This is likely to be due to the small numbers of objects involved.

3. MODELING THE POLLUTION

To model the pollution we follow Murray et al. (2001). The outer layers of the star are assumed to be well mixed down to a depth that depends on the mass and bulk metallicity of the star. For stars less massive than 1.2 $M_\odot$, the mass of this mixed layer is assumed to be given by the mass of the surface convection zone. For more massive stars, Murray et al. used the observed lithium abundances of open clusters to infer the mass of the surface mixing layer. Briefly, the abundance of lithium as a function of stellar mass (or effective temperature) shows a dramatic dip around 1.4 $M_\odot$ (Boesgaard & Tripicco 1986). The dip is believed to be due to the thermonuclear destruction of lithium at depths where the temperature exceeds $\sim 3 \times 10^6$ K. This strongly suggests that surface material is mixed down into the star well below the bottom of the convection zone, which is very thin in a 1.4 $M_\odot$ star. Murray et al. describe a crude empirical model for the depth of this surface mixing layer as a function of stellar mass and composition; we use that model in this section.

The stars in the Murray et al. sample show a distinct jump in [Fe/H] around 1.5 $M_\odot$, just above the lithium dip (the open squares in Fig. 7). They argue that the stars in their sample, the bulk of which are not known to have Jupiter-mass planets, have accreted iron-rich material after having reached the main sequence. Using their model for the depth of the mixing layer, they compare Monte Carlo simulations of polluted stellar populations to the observed mass-metallicity distribution to infer that, on average, the stars in their sample have accreted $\sim 0.4\ M_\oplus$ of iron. (We reproduce the result in Fig. 10.)

The Hertzsprung gap stars afford a test of this conclusion. If most stars are polluted, then when they evolve and develop or deepen surface convection zones, their metal-rich surface layers will be mixed with the relatively metal poor inner layers, reducing the surface iron abundance. As can be seen from Figure 10, the Hertzsprung gap stars (shown as open triangles) are metal-poor compared to unevolved stars of the same mass. However, Greg Laughlin (2001, private communication) has pointed out two selection effects that the Murray et al. sample might suffer from.

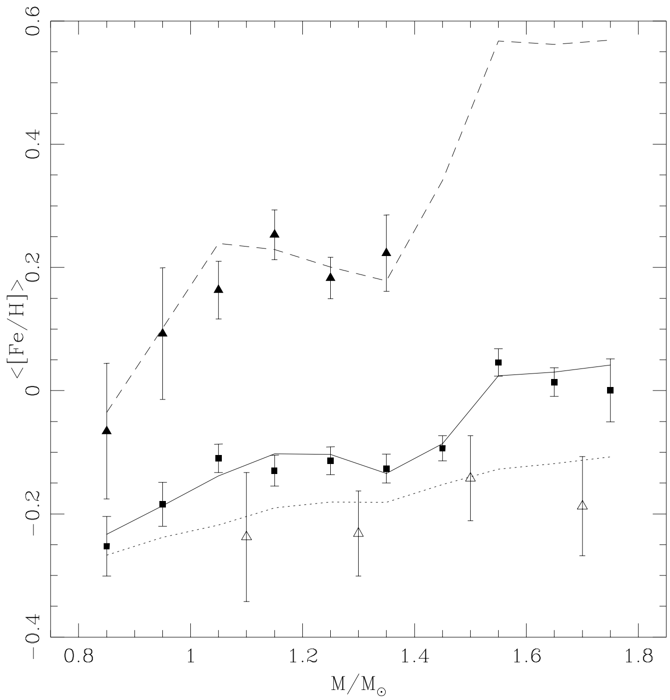

FIG. 10.—Average metallicity of three populations of Monte Carlo polluted stars compared with the three different observed distributions. The solid curve is a model in which stars accrete a Gaussian-distributed amount of iron with mean 0.4 $M_{\oplus}$. It is a best-fit model for the Murray et al. (2001) sample, shown by the filled squares. No cutoff in $B-V$ has been applied to the model or the data. The dotted line shows the same model, except that the surface-mixing region is assumed to have deepend by a factor of 10 (in mass); it gives an acceptable fit to the Hertzsprung gap stars. The dashed curve shows a model in which stars have accreted 6.5 $M_{\oplus}$ of iron on average. It gives an acceptable fit to the sample of stars with planets.

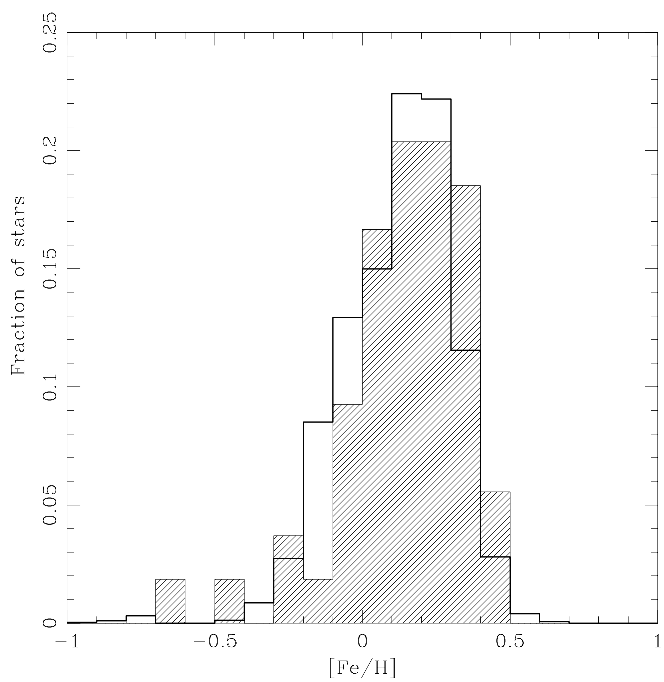

FIG. 11.—Comparison between the [Fe/H] histogram of known stars with planets and the result of a Monte Carlo experiment in which iron is added to the envelopes of a population of unpolluted stars. The unpolluted population is that described in Murray et al. (2001). The mean added iron mass is found by optimizing the fit of [Fe/H] as a function of stellar mass (see Fig. 10) and is 6.5 $M_{\oplus}$. We assume variance of 1/3 the mean, or $\sim 2.2\ M_{\oplus}$.

The most dramatic difference between the dwarf and subgiant stars occurs for masses larger than about 1.5 $M_{\odot}$. The first point is that low-metallicity dwarfs in this mass range are very hot, making metallicity determinations difficult, whereas the subgiants are fairly cool, so that the latter might be overrepresented relative to the former. This is essentially the $B-V$ selection effect in a slightly different guise. The second point is that low-metallicity giants will be brighter than high-metallicity giants, and hence will tend to be overrepresented in any magnitude-limited sample; this is the V selection effect again.

Figure 10 also shows that a polluted model can fit all three data sets (including the stars-with-planets sample) with only one free parameter, the average mass of accreted material. The unpolluted model is shown by the dotted line, which passes through the error bars associated with the Hertzsprung gap stars. As mentioned above, the solid line, which is a best-fit model for the unevolved stars in the Murray et al. sample, corresponds to an average mass of accreted iron of 0.4 $M_{\oplus}$. The dashed line running through the stars-with-planets data corresponds to a model with an average of 6.5 $M_{\oplus}$ of accreted iron. This plot makes a clear prediction: stars above $\sim 1.5\ M_{\odot}$ that have short- to moderate-period Jupiter-mass planets will have very high metallicities. The plot suggests [Fe/H] of the order of 0.5.

We caution that this prediction assumes that our unpolluted models are good representations of stars that have surface layers much more metal rich than their interiors (by about 0.5–0.7 dex). This assumption must be checked using polluted models. Nevertheless, we feel that stars with short-period Jupiters having masses larger than $\sim 1.5\ M_{\odot}$ will have metallicities [Fe/H] substantially above 0.2 dex.

The same Monte Carlo models yield the histogram of polluted stars shown in Figure 11. The model is shown by the open histogram, on which is superimposed the histogram of stars with planets. In both samples we include only stars less massive than 1.45 $M_{\odot}$, since there are only two stars in the stars-with-planets sample more massive than this value. The agreement is excellent.

Finally, the Monte Carlo models give the run of average [Fe/H] with age. The solid lines in Figure 8 show the results. We see that the model with 0.4 $M_{\oplus}$ of added iron gives a good fit to the Murray et al. sample, while the model with 6.5 $M_{\oplus}$ of added iron fits the stars-with-planets data. We stress that the underlying (unpolluted) variation of metallicity with stellar age is the same in both Monte Carlo models. Thus, pollution can explain the variation of [Fe/H] with mass and the variation of [Fe/H] with stellar age in both samples.

This result bolsters our confidence that the stars-with-planet sample has suffered a substantial amount of pollution.

4. DISCUSSION

Four recent papers (Laughlin 2000; Santos et al. 2000, 2001; Gonzalez et al. 2001) have presented figures similar to the top panel of our Figure 5. Laughlin also shows data for photometrically determined [Fe/H] as a function of stellar mass, much like the bottom panel of Figure 5. Both Laughlin and Gonzalez et al. conclude that the data are consistent with pollution of the outer envelopes of the stars with planets by iron-rich material *after the stars have reached the main sequence.*

In contrast, Santos et al. (2000) tentatively conclude that the data "support the idea that a star needs to be formed out of a metal-rich cloud to form giant planets." Santos et al. (2001) argue that their results rule out pollution.

In view of the fact that there are now seven stars with planets having [Fe/H] < -0.05 and that four of these have [Fe/H] < -0.2, the statement that a star needs to be born in a metal-rich cloud to form giant planets seems unwarranted. It may well be, however, that the planet formation rate (Lissauer 1993), or the probability of migration (Murray et al. 1998), or both, are strong functions of initial [Fe/H]. This would lead to a positive correlation between [Fe/H] and the fraction of stars that harbor planets, a correlation that is seen in the data of Santos et al. However, this would not explain the trend of rapidly increasing [Fe/H] with increasing stellar mass seen in Figure 10. The question then becomes, is this trend real, and if so, is it the result of pollution? As more planets are discovered, the answer, at least to the former query, will become clear.

Pinsonneault, DePoy, & Coffee (2001) argue that planetesimal accretion would result in extremely high [Fe/H] for massive, high-$T_{\rm eff}$ stars with planets, if low- and high-mass stars accreted similar amounts of material. This would be true if the surface mixing region were limited to the surface convection zone. They go further, however, and assert that it is true even if one accounts for rotational mixing. To back up this assertion, they evolve a star of 1.2 $M_\odot$ with an initial [Fe/H] $= 0.2$; at a hundred million years of age, the convection zone had a mass of 0.006 $M_\odot$ and contained 4.12 $M_\oplus$ of iron. *They then added* 37 $M_\oplus$ *of iron!* This yielded a star with [Fe/H] $= 1.2$. Following the subsequent evolution, including a prescription for rotationally enhanced mixing, they find that [Fe/H] is reduced from 1.2 to ~ 0.9, much higher than any known star with planets.

A more reasonable test would be to assume an enhancement of ~ 3 to 6 $M_\oplus$; this would increase the surface metallicity to 0.44–0.6 dex. If the rotational mixing reduces this by $\sim 30\%$, the result would be a star with [Fe/H] $= 0.28$–0.45, slightly higher than the average [Fe/H] that is seen in this mass range, although such high metallicities are seen. Still more reasonable would be to take an initial [Fe/H] $= 0$, similar to what is seen for low-mass stars with planets (see Fig. 5). Then the post-pollution [Fe/H] $= 0.5$, even for 6 $M_\oplus$ of added iron, and rotational mixing would reduce this to 0.4 dex or less. Finally, if we assume that the stars-with-planets sample has an intrinsic metallicity like that of the Murray et al. sample, the result is Figure 10.

From Figure 5 we see that the distribution of metallicity for stars with $0.75 \lesssim M_* \lesssim 0.95$ is only marginally higher for stars with planets than for stars without (known) planets. From Figure 7 we see that the average metallicity rises with mass for both classes of stars, although it rises much more rapidly for stars with planets. In contrast, it rises only very slowly for Hertzsprung gap stars. Murray et al. argue that the rise seen in their sample arises partly from pollution and partly from the fact that less massive stars tend to be older than more massive stars (the "age-mass relationship"), and older stars tend to be metal-poor.

We note that the age-mass relationship we find for the stars-with-planets sample is very similar to that of the Murray et al. sample, yet the [Fe/H] versus stellar mass relation for the stars-with-planets sample rises much more rapidly than that of the Murray et al. sample. We have shown above that accretion of 6.5 $M_\oplus$ of iron will produce such a rise. In the absence of a known selection effect capable of producing such a dramatic trend, this suggests that the stars with planets have accreted substantial amounts of iron-rich material.

Santos, Israelian, & Mayor (2001) also show, in their Figure 4, a histogram of stars with planets together with a sample in which they added 15 $M_\oplus$ of iron to their sample of 43 stars with low limits on K (that is, stars that do not have Jupiter-mass planets in short- to moderate-period orbits). They restricted their stars to have mass less than 1.2 $M_\odot$. They find that there are too many "polluted" stars at high values of [Fe/H], compared to the stars-with-planets sample, and that the steep fall at the high-metallicity end of the distribution is not reproduced. They conclude that a simple pollution model cannot explain the observations.

Our results, illustrated in Figures 10 and 11, contradict this statement. The main differences appear to be that Santos et al. (2001) added 15 $M_\oplus$ of iron, about 3 times the amount added in our best-fit model, and that they took a smaller mass (equal to the mass of the convection zone) for the surface mixing layer of even their most massive stars. Since the iron content of the convection zone of their 1.2 $M_\oplus$ star of solar metallicity is about 1.4 $M_\oplus$, they find stars with [Fe/H] approaching unity when they add 15 $M_\oplus$ of iron. Our models use a slightly more massive surface-mixing layer for stars above 1.2 $M_\odot$ (taken from an empirical fit to lithium abundance data; see Murray et al. 2001). More importantly, we add less iron, so we do not find many stars with metallicities above 0.5 dex.

Santos et al. (2001) also plot [Fe/H] versus mass (their Fig. 5) for their sample of planetless dwarfs. The latter sample shows a lower envelope of increasing [Fe/H] with increasing mass, which tracks the lower envelope of the stars with planets. In contrast, as can be seen in our Figure 5, while we see a lower envelope that increases with increasing mass in our sample, it has a much lower value of [Fe/H] at any given stellar mass. Clearly, their sample of dwarfs differs from the one we employ.

In fact, a quick check shows that all but two stars in the Santos et al. (2001) planetless sample satisfy $B-V > 0.56$. The bluest star has $B-V = 0.51$; it appears as an outlier in the lower right-hand corner of their Figure 5. Had they allowed for planetless stars as blue as 0.48 (as found in the stars-with-planets sample, and applied to the stars in the Murray et al. sample as plotted in Fig. 5), they would have seen many planetless stars at every mass having [Fe/H] much lower than the stars-with-planets sample.

The peculiar behavior of [Fe/H] with stellar age for the stars-with-planets sample is a second indication that pollution has occurred in these stars. Restricting $B-V$ to be larger than 0.48 (as shown by the open squares in the bottom panel of Fig. 8), or even 0.55 in the Murray et al. sample, does not produce the very sharp rise at ages around 10 Gyr. However, the polluted model that fits the [Fe/H] versus mass data naturally produces a good fit to the [Fe/H] versus stellar age data.

As pointed out in Murray et al. (2001), slightly evolved (or Hertzsprung gap) stars offer a possible test of the pollution scenario; they should have, on average, lower metallicities if most stars are polluted. Our fits to evolutionary tracks show that only one star in the current stars-with-planets sample, HD 38529, is such a star; this star can be seen in the Hertzsprung gap in Figure 1. HD 38529 has a rather high [Fe/H] $= 0.37$. We conclude that at least some

of the high metallicities seen in this sample are likely to be due to a high primordial metallicity. We stress, however, that high primordial metallicities are not required to produce radial velocity planets, nor will they produce the steep trend in [Fe/H] seen in the low-mass stars. More stars with planets will be discovered in the Hertzsprung gap as the radial velocity surveys proceed, which will allow an unbiased test of the pollution scenario.

4.1. *Giant Planet Accretion, or Planetesimal Accretion?*

Laughlin & Adams (1997) showed that accretion of Jupiter-mass planets pushed into their parent stars during the lifetime of the protoplanetary disk would produce little or no pollution of low-mass stars. However, Lin (1997) has speculated that Jupiter-mass bodies may be accreted after the gas disk has dissipated. We argue that such a scenario is unlikely to explain the difference between the stars-with-planets sample and the Murray et al. sample, assuming that the steep increase in [Fe/H] in the former is not a selection effect.

Figure 6 demonstrates that the elevated metallicities seen in the stars with planets does not require the presence of a very short period Jupiter; nine of the systems with [Fe/H] > 0.2 exhibit innermost planets having semimajor axes exceeding 1 AU, and several have $a > 2$ AU. HD 27442 is a solar-mass star ($M_* = 1.06\ M_\odot$) with a planet of mass $M \sin i = 1.42\ M_J$ at 1.18 AU on a nearly circular orbit; the star has [Fe/H] $= 0.2$. If this star ingested a Jupiter-mass planet, it did so without the aid of the remaining planet.

Figure 5 shows that there is a distinct shortage of low-metallicity stars with planets having masses greater than about 0.9 $M_\odot$. If this is due to pollution, then essentially every star with planets is polluted; if a significant fraction were not polluted, then we would see some low [Fe/H] but slightly evolved high-mass stars with planets as well as unevolved low-mass stars with planets closer to the $B-V$ cutoff.

Our models show that the average amount of accreted iron in the stars-with-planets sample is of the order of 5 $M_\oplus$. In contrast, no more than about 10% of the stars in the Murray et al. sample could have accreted that much material, or the distribution of [Fe/H] would be double peaked, contradicting the observations.

The tight correlation between the presence of a radial velocity planet and the accretion of several Earth masses of iron is difficult to explain as the result of the accretion of a Jupiter-mass body. It requires that most or all stars with radial velocity planets accrete Jupiter-mass bodies (after 10–20 Myr) independent of the semimajor axis of the remaining planet(s), while less than 20% of stars lacking radial velocity planets do so. (Note that the rather weak metallicity mass trend found by Murray et al. shows that no more than 10%–20% of stars lacking radial velocity planets could have accreted a Jupiter-mass planet with the metallicity of Jupiter.)

It is difficult to believe that the presence of a Jupiter-mass planet at 1–3 AU, as seen in several systems, can ensure the accretion of a second Jupiter-mass planet. We note that our own Jupiter, at 5.2 AU, almost certainly did not cause the accretion of any Jupiter-mass objects onto our Sun 20 Myr after it formed.

On the other hand, Jupiter did cause the accretion of a substantial mass of asteroids onto the Sun, of the order of (2–3) $M_\oplus$. It is likely that Jupiter migrated inward $\sim$0.1 AU during the ejection of interplanetary material, but the presence of the inner asteroid belt, as well as the regular orbits of both Jupiter and Saturn, suggest that Jupiter did not migrate several AU.

The small orbits of the currently known extrasolar planets are consistent with the notion that they migrated inward several AU. If there was a massive planetesimal disk inside the original location of these planets, a substantial fraction of the order of 5%–10% of the material in the disk would have been dropped on the star (Murray et al. 1998, 2002; Quillen & Holman 2000) as a result of resonant interactions between the planet and the planetesimals. If the migration proceeds to very small semimajor axes ($\lesssim 0.2$ AU), a second process becomes efficient, namely, scattering of planetesimals by the planet onto the star. This will add another $\sim$5%–10% of the disk mass onto the star (Murray et al. 1998; Hansen, Murray, & Holman 2001).

If the planetesimal disk is *responsible* for the inward migration (Murray et al. 1998), then the amount of accreted material will be larger for more massive planets. This effect should be most dramatic in more massive stars, since they have less massive surface mixing regions. A plot of [Fe/H] versus $M \sin i/M_J$, for stars more massive than 0.8 $M_\odot$ (Fig. 12) does hint at such a trend of increasing metallicity with increasing mass, but the trend is significant only at the 2 σ level. Increasing the size of the stars-with-planets sample will allow this question to be answered more definitively.

Another possible signature of planetesimal accretion is the relative enhancement of volatile (e.g., C, N) versus refractory (Fe, Ni) elements. Asteroids and terrestrial planets are depleted in noble gases; terrestrial planets (but not most asteroids) are also strongly depleted in elements such as

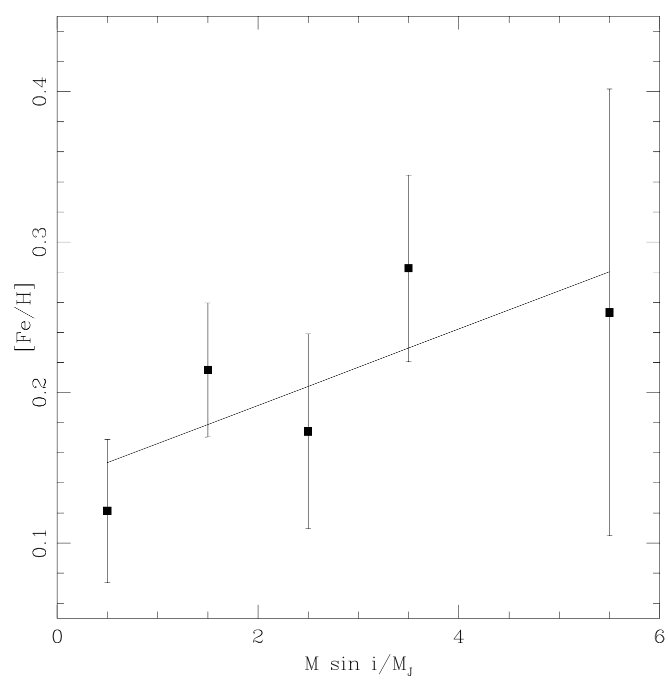

FIG. 12.—Average metallicity of the stars with planets, binned by $M \sin i$ of the planet. The stars are required to be more massive than 0.80 $M_\odot$, since the convection zones of less massive stars are too deep to show significant pollution. There is a hint of an increase in [Fe/H] with increasing planetary mass. The straight line is a least-squares fit, [Fe/H] $= a(M \sin i/M_J) + b$, with $a = 0.025 \pm 0.012$.

carbon, presumably because they formed from material that condensed at high temperatures. By contrast, Jupiter and the other giant planets in our solar system are carbon-rich; (they are presumably also iron-rich, but there is no direct evidence). Thus, accreting material that condensed very close to the star would enhance the iron abundance, but not the carbon abundance. Accreting rocky material that formed farther from the star would enhance both carbon and iron, as would the accretion of Jupiter.

We conclude that stars having radial velocity planets in orbits of order 0.2 AU or smaller are likely, in the planetesimal accretion scenario, to have accreted material that is rich in refractories such as iron and magnesium, but volatile-poor, since the planetesimals in such small orbits condense from the protoplanetary disk at high temperatures. There is some evidence indicating that this is the case (Smith et al. 2001; but see also Takeda et al. 2001).

5. CONCLUSIONS

Previous work has shown that stars possessing radial velocity planets appear, on average, to be metal-rich compared to field stars of the same mass and age (Gonzalez 1997; Laughlin 2000; Santos et al. 2000; Gonzalez et al. 2001). We confirm this result. Our work has emphasized that part of this difference is due to a color selection effect: the stars with planets appear to be drawn from a sample chosen to have $B-V > 0.48$ (or 0.56 in the case of the sample presented in Santos et al. 2001). As a result, the high-mass stars included in the present surveys *must* have high metallicity, skewing the distribution of [Fe/H] in the resulting sample of stars with planets.

However, we have shown that this color cutoff does not affect stars with $M_* \leq 1.1\ M_\odot$; even for the subset of stars less massive than this, the stars with planets still have higher average metallicity than our control sample. Applying the same $B-V$ cutoff to the control sample does in fact increase the average [Fe/H] of the high-mass stars, but not by enough to explain the difference between the two samples. We conclude that the high metallicity of the stars-with-planets sample is not due entirely to the color-selection effect. Nor is the steep rise in [Fe/H] as a function of stellar mass in the range $0.8 < M_* < 1.1\ M_\odot$, or the lack of a trend in [Fe/H] as a function of stellar age, explained by the color selection effect.

The fact that the Murray et al. sample is more severely magnitude limited than the stars-with-planets sample suggests that the steep rise in [Fe/H] with mass in the latter is not simply due to a V selection. Similarly, none of the observational results discussed here appears to be explained by a K selection effect. However, it is clear that both questions need more work, primarily in the form of better sample selection.

Our Monte Carlo simulations of pollution show that all three observations (high average [Fe/H], rapid increase in [Fe/H] with stellar mass, and the lack of a trend in [Fe/H] with age) can be produced by the addition of $\sim 5\ M_\oplus$ of iron to those stars that have radial velocity planets.

Laughlin (2000) has pointed out that measurements of [Fe/H] in those stars with planets having stellar companions can be used to test the pollution hypothesis. We point out another test, examining stars with planets in the Hertzsprung gap. The one star in the current sample that resides in the gap is metal-rich, suggesting that its bulk metallicity is high; no pollution is required for this object, although it might have had an even higher (apparent) metallicity while on the main sequence.

A third test will be provided by the discovery of planets around stars more massive than $\sim 1.6\ M_\odot$. Since high-precision radial velocity measurements are difficult for such hot stars, other techniques, such as transit or astrometric detections, will have to be developed; if pollution is occurring on the scale suggested here, these stars should be very metal rich. Further theoretical work is needed to determine exactly how metal-rich they should be.

We argued that any accreted iron is unlikely to have been added in the form of a gas giant planet and suggested that trends in the abundances of volatile versus refractory elements can be used to distinguish between gas giant accretion and planetesimal accretion (Smith et al. 2001). A second trend, namely, higher [Fe/H] in systems with more massive planets, as hinted at in Figure 12, could also be used to distinguish between planetesimal accretion and gas giant accretion. Establishing the reality of either trend would strongly suggest that pollution plays a significant role in such systems.

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REFERENCES

Boesgaard, A. M., & Tripicco, M. J. 1986, ApJ, 302, L49
Castro, S., Rich, R. M., Grenon, M., Barbuy, B., & McCarthy, J. K. 1997, AJ, 114, 376
Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45
Fischer, D. A., Marcy, G. W., Butler, R. P., Vogt, S. S., & Apps, K. 1999, PASP, 111, 50
Gonzalez, G. 1997, MNRAS, 285, 403
———. 1998, A&A, 334, 221
Gonzalez, G., & Laws, C. 2000, AJ, 119, 390
Gonzalez, G., Laws, C., Tyagi, S., & Reddy, B. E. 2001, AJ, 121, 432
Gonzalez, G., & Vanture, A. D. 1998, A&A, 339, L29
Gonzalez, G., Wallerstein, G., & Saar, S. H. 1999, ApJ, 511, L111
Hansen, B., Murray, N., & Holman, M. 2001, ApJ, submitted
Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, ApJ, 529, L41
Laughlin, G. 2000, ApJ, 545, 1064
Laughlin, G., & Adams, F. C. 1997, ApJ, 491, L51
Lin, D. N. C. 1997, in IAU Colloq. 163, Accretion Phenomena and Related Outflows, ed. D. Wickramasinge, B. V. Bicknell, & L. Ferrario (ASP Conf. Ser. 121; San Francisco: ASP), 321
Lissauer, J. J. 1993, ARA&A, 31, 129
Marcy, G. W., Cochran, W. D., & Mayor, M. 2000, in Protostars and Planets IV, ed. V. Mannings, A. Boss, & S. S. Russell (San Diego: Academic Press), 1285
Murray, N., Chaboyer, B., Arras, P., Hansen, B., & Noyes, R. W. 2001, ApJ, 555, 801
Murray, N., Hansen, B., Holman, M., & Tremaine, S. 1998, Science, 279, 69
Murray, N., Paskowitz, M., & Holman, M. 2002, ApJ, in press (astro-ph/0104475)
Pinsonneault, M. H., DePoy, D. L., & Coffee, M. 2001, ApJ, 556, L59
Quillen, A. C., & Holman, M. 2000, AJ, 119, 397
Santos, N. C., Israelian, G., & Mayor, M. 2000, A&A, 363, 228
———. 2001, A&A, 373, 1019
Smith, V. V., Cunha, K., & Lazzaro, D. 2001, AJ, 121, 3207
Takeda, Y., Sato, B., Kambe, E., Aoki, W., Honda, S., Kawanomoto, S., Masuda, S., Izumiura, H. Watanabe, E., et al. 2001, PASJ, in press (astro-ph/0109245)