POSSIBLE STELLAR METALLICITY ENHANCEMENTS FROM THE ACCRETION OF PLANETS

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ABSTRACT

A number of recently discovered extrasolar planet candidates have surprisingly small orbits, which may indicate that considerable orbital migration takes place in protoplanetary systems. A natural consequence of orbital migration is for a series of planets to be accreted, destroyed, and then thoroughly mixed into the convective envelope of the central star. We study the ramifications of planet accretion for the final main-sequence metallicity of the star. If maximum disk lifetimes are on the order of ~ 10 Myr, stars with masses near 1.0 \( M_\odot \) are predicted to have virtually no metallicity enhancement. On the other hand, early F- and late A-type stars with masses \( M_\star \approx 1.5–2.0 \ M_\odot \) can experience significant metallicity enhancements due to their considerably smaller convection zones during the first 10 Myr of pre–main-sequence evolution. We show that the metallicities of an aggregate of unevolved F stars are consistent with an average star accreting ~ 2 Jupiter-mass planets from a protoplanetary disk having a 10 Myr dispersal time.

Subject headings: stars: abundances — stars: stellar statistics — stars: planetary systems

1. INTRODUCTION

The detection of planets orbiting nearby solar-type stars (e.g., Mayor & Queloz 1995) was a much-anticipated discovery. The existence of massive planets at small orbital radii \( r \leq 0.1 \) AU, however, came as a surprise. The first such system found—51 Peg—has a planetary mass \( M_p \sin i = 0.47 \) Jupiter masses \( (M_p) \) and a semimajor axis \( r = 0.05 \) AU (Marcy & Butler 1996). Similar close companions have been detected around \( \upsilon \ And (M_p \sin i = 0.68 \ M_p, r = 0.057 \) AU), 55 Cnc \( (M_p \sin i = 0.84 \ M_p, r = 0.11 \) AU), and \( \tau \ Boo (M_p \sin i = 3.87 \ M_p, r = 0.0462 \) AU) (see Butler et al. 1997).

The existence of Jupiter-mass planets very close to their primary stars strongly suggests that orbital migration has occurred in these systems. The planets are posited to have formed at large radii \( (5–10 \) AU, where most of the disk mass resides) and thereafter to have been transported inward as a result of tidal interactions with the protoplanetary disk. Successful models of orbital migration have been constructed (e.g., Lin, Bodenheimer, & Richardson 1996; Trilling et al. 1997) that demonstrate the plausibility of this hypothesis.

As a natural consequence of the migration scenario, a series of planetary-mass objects might be added to the star during its pre–main-sequence development (Gonzalez 1997a, 1997b; Lin 1997; Jeffery, Bailey, & Chambers 1997). Because the accreted planets are (presumably) metal rich, the metallicity of the parent star is enhanced. The degree of metallicity increase depends sensitively on the fraction of the star over which accreted planets are distributed. A planet added to a fully convective star is folded into the entire stellar mass and leads to a negligible metallicity enhancement. If the parent star is largely radiative, with only a small outer convective zone, metallicity enhancements can be much larger. If the convective envelope subtends 2% of the mass of a 1 \( M_\odot \) star, and the star accretes a Jupiter-like planet, the metal enhancement \( \Delta Z \sim 0.005 \) is both significant and observable.

As a general trend, solar-type stars begin their pre–main-sequence evolution on the Hayashi track with a fully convective stellar configuration. After several million years, radiative cores appear and the size of the convective envelope steadily decreases over the next 10 Myr or so. Main-sequence solar-mass stars have relatively small outer convection zones which comprise only a few percent of the stellar mass. ZAMS stars with masses greater than \( \sim 1.3 \ M_\odot \) are radiative up to the surface. The expected lifetimes for protoplanetary disks lie in the range 1–10 Myr, indicating that early F stars are likely to exhibit a metallicity trend resulting from the accretion of planets.

This Letter is organized as follows. In § 2 we outline the basic theoretical issues involved in determining stellar metallicity enhancements arising from the accretion of planets. We then use these considerations in § 3 to examine a sample of nearby F stars. We conclude in § 4 by discussing our results and their implications.

2. METALLICITY ENHANCEMENT THROUGH ACCRETION OF PLANETS

The metallicity of the convective envelope of a young star will evolve as it accretes planets. In this section we develop a simple model of this process. For the sake of definiteness, we assume that the accretion of Jupiter-type planets is determined by an accretion function \( F(t) \) that specifies the mass in planets accreted per unit time. Planets, of course, are discrete objects, so the continuous function \( F(t) \) applies to an ensemble average of systems rather than particular individual systems. The range of possibilities is adequately covered if we use a class of accretion functions having the general form

\[
F(t) = F_0 [1 - (t/t_0)]^n,
\]

which defines a three-parameter family. The constant \( F_0 \) sets the overall normalization; the time constant \( t_0 \) is the total time interval over which planets are accreted; the index \( n \) is a shape parameter that specifies how planet accretion falls off over time.

The total mass in planets accreted over the entire time interval is given by

\[
\Delta M = \frac{F_0 t_0}{n + 1},
\]

and the mean number of accreted planets is \( N_p = \Delta M/M_p \), where \( M_p \) is the mean mass of the planets. The time \( t_0 \) is determined by the lifetime of the circumstellar disk. When the
disk mass becomes too small, orbital migration can no longer operate and planets will no longer be accreted. Expected disk lifetimes are 1–10 Myr, with considerable variation and uncertainty (see, e.g., the review of Strom, Edwards, & Skrutskie 1993).

Notice that rocky debris will also be accreted at some level. The inward spiral of a gas giant is likely to enforce the accretion of rocky material inside its orbit (assuming the evolution is roughly similar to that of our solar system). However, our numerical experiment is limited to Jupiter-like planets.

The differential equation describing the metallicity $Z$ of the convective envelope of a particular star as a function of time can be written as

$$\frac{dZ}{dt} = (Z_P - Z) \frac{F(t)}{M_c(M_e, Z, t)}, \quad (3)$$

where $M_c$ is the mass of the convective envelope as a function of time. We assume that the stellar mass $M_\star$ does not change appreciably as planets are subsumed. We expect that the metallicity $Z_\star$ of the planets will be comparable to that of Jupiter, and hence $Z_\star \approx 0.1$. We also implicitly assume that the distribution of heavy elements in the accreted planets is the same as the distribution of heavy elements in the Sun.

The three-dimensional function $M_c(M_\star, Z, t)$ must be obtained from stellar evolutionary calculations. Using a grid of pre–main-sequence tracks (Forestini 1994) for model stars of mass $M_\star = 1.0-2.5 M_\odot$ at metallicities $Z = 0.02$ and 0.04, we construct the following analytic expression for the mass of convective envelopes:

$$M_c(M_e, Z, t) = M_e(1 - x^2) e^{-x}, \quad (4)$$

where we have defined

$$x = \frac{tM_e^{3.1}}{40[1 + 15(Z - 0.02)]}. \quad (5)$$

This smoothly varying function reproduces the calculated values of $M_c(M_e, Z, t)$ to the required accuracy. It provides accurate values for both the evolutionary time required to obtain a particular star’s ZAMS convective envelope, and also the mass of that envelope.

The predicted effect of accreted planets on main-sequence metallicities is illustrated in Figure 1, where several numerical solutions to equation (3) are plotted. Our “reference case” uses representative values $t_0 = 10$ Myr, $\Delta M = 2M_\star$, and shape parameter $n = 2$. When planets are accreted onto a fully radiative star, the planet’s mass $M_P$ (taken to be $1 M_\star = 0.001 M_\odot$) is assumed to mix with an additional mass $4M_\odot$ of the parent star’s envelope. Figure 1 indicates that the disk lifetime $t_D$ is the most sensitive parameter. In particular, if the timescale for disk dispersal is $\sim 1$ Myr, then no metallicity trend from planetary accretion should be discernible in a sample of stars in the mass range $M_\star = 1.0-2.5 M_\odot$.

3. A SEARCH FOR A METALLICITY TREND IN THE NEARBY F STARS

To examine the plausibility of the planetary accretion scenario, we have used a catalog of nearby F stars (Marsakov & Shevlenet 1995, hereafter MS) to search for trends in metallicity. The MS catalog is based on the compilation of Hauck & Mermilliod (1985), and contains 5489 F stars within 80 pc of the Sun. The MS data set lists coordinates and kinematical properties for each star, along with metallicities (as [Fe/H]), effective temperatures, absolute magnitudes, ages,1 and other data. MS determine [Fe/H] from $uvby$ photometric measurements using the calibration of Carlberg et al. (1985). We have found that this calibration introduces a slight (positive) correlation between metallicity $Z$ and temperature $T_{\text{eff}}$. We use an alternative calibration (Schuster & Nissen 1989), which does not exhibit such a correlation, as determined by comparing the [Fe/H] values with measurements obtained via high-resolution spectroscopy (Rocha-Pinto & Maciel 1996; Wyse & Gilmore 1995). In reanalyzing the metallicities for each star in the MS catalog, we use $uvby$ photometry taken directly from the Hauck & Mermilliod (1985) compilation. The uncertainty in this method of determining metallicity for each star is 0.16 dex (Schuster & Nissen 1989).

MS state that their data set is “practically full” in the 80 pc limiting volume for stars having corrected colors $b - y < 0.32$ (2017 stars), and 60% full over the entire F2–G2 spectral interval (5800 K $< T_{\text{eff}} < 7000$ K). Because the locus of stars having $b - y = 0.32$ does not correspond to a perfectly vertical line in a $Z$ versus $T_{\text{eff}}$ diagram, we seek to avoid complications introduced by incompleteness by accepting only catalog stars lying within a distance $d = 40$ pc. We also reject from consideration all stars belonging to unresolved binaries.

1 The ages are based on pre-HIPPARCOS parallaxes.
Accreted planets generate a trend in the metallicity of stars as a function of mass rather than effective temperature. We must thus determine the stellar mass as a function of metallicity and temperature, i.e., $M_*(Z_T)$. For a given effective temperature and metallicity, we make bilinear interpolations from the ZAMS models (Forestini 1994) to obtain the stellar mass. The MS data set is binned according to effective temperature (all the F stars), rather than mass. The lower end of the $T_{\text{eff}}$ range (5800–7000 K) probes down to metal-poor solar-mass stars, whereas the high end of the $T_{\text{eff}}$ range includes metal-rich stars with masses up to $\sim 1.8 M_\odot$. However, only a small range in mass (1.42–1.52 $M_\odot$) is represented over the entire range of metallicities in the sample.

In order to search the MS stars for a specific metallicity enrichment trend, as predicted by equation (3), we perform Monte Carlo simulations that add individual planets to an ensemble of stars in accordance with particular choices for the accretion function. The metallicity trend in the simulated stellar distribution can then be compared with the trend present in the MS catalog stars.

We selected 1000 stars in the mass range $1.0 M_\odot < M_* < 2.5 M_\odot$ by sampling from a Gaussian distribution with variance $0.6$ by sampling the initial mass function (Salpeter 1955). These stars were then assigned metallicities in accordance with the metallicity distribution for G dwarfs in the solar neighborhood having $\text{[Fe/H]} \geq -0.4$ (Rocha-Pinto & Maciel 1996). The metallicities in their observed distribution were obtained from $uvby$ photometry and the Schuster & Nissen (1989) calibration, just as we have done. Because G star progenitors are largely convective during the $\sim 10$ Myr disk dispersal time, they should not exhibit an overall metallicity trend from the accretion of Jupiter-type planets. Indeed, the analysis of Rocha-Pinto & Maciel (1996) reveals no significant trend.

The 1000 stars were allowed to accrete planets in accordance with the distribution given by equation (1). The masses of individual accreted planets were allowed to vary about the mean value of $1 M_J$ by sampling from a Gaussian distribution with variance $M_J/3$. The number of planets ingested by each star was sampled from a Gaussian distribution with variance $\frac{1}{2}$ centered on $N_p = 2$ (rounding the sample to the nearest integer). The times at which planets were accreted were sampled directly from equation (1), with $n = 2$ and $t_p = 10$ Myr. The accreted planets (with $Z_p = 0.1$) were assumed to mix thoroughly with the convective stellar envelope, enhancing its metallicity. In the first simulation, planets entering fully radiative stars were assumed to mix with $4 M_J (0.004 M_\odot)$ of the subphotospheric stellar material (this value is consistent with numerical estimates of G. Bryden 1997, private communication).

The distribution of metallicity-enhanced stars is shown in Figure 2. After planetary accretion takes place, only 291 stars fall in the domain shown, i.e., $6000 \, \text{K} < T_{\text{eff}} < 7000 \, \text{K}$ and $0.01 < Z < 0.06$. The arrows connect the $(Z, T_{\text{eff}})$ value that each star would have with no planet accretion with the $(Z, T_{\text{eff}})$ value obtained after including planet accretion. The figure also shows the zero-age F stars in the MS catalog that have distances $d < 40$ pc and fall within the plot limits (305 stars). We have used only unevolved stars (MS catalog stars whose ages are consistent with a ZAMS identification) in order to minimize the complications brought on by both main-sequence stellar evolution and the overall metallicity evolution of the Milky Way.

A linear fit to the original metallicities of the 291 simulation stars shows a slight positive slope of $(0.6 \pm 0.8) \times 10^{-6}$ K$^{-1}$. A linear fit to the distribution of enhanced metallicities shows a larger slope of $2.5 \times 10^{-6}$ K$^{-1}$, which is consistent with and comparable to the slope of $(1.8 \pm 1.7) \times 10^{-6}$ K$^{-1}$ obtained from the 305 MS catalog stars.

In Figure 3 we show the results of a simulation which contains the same parameters as the simulation described above, except that we have changed the minimum mixing mass to $2 M_J$. Notice that this simulation predicts too many high-metallicity stars compared to the MS data set. We can thus conclude that accreted planets must mix with more than $2 M_J$ of stellar material, or that less than two planets per star can be accreted.

4. DISCUSSION

We have studied the possible enhancement of stellar metallicity due to the accretion of planets. In particular, we have developed a simple theoretical model to incorporate metal enhancements due to accreted planets. We have then searched for trends in metallicity within a well-defined sample of nearby F stars. Our results are summarized below.

1. The effects of planet accretion on stellar metallicity are strongly dependent upon the total stellar mass. Stars with masses comparable to that of the Sun have large convective envelopes for nearly the entire time interval over which planets are expected to be accreted. These stars will show essentially no metal enhancements. Higher mass stars, with $M_* \sim 1.5 M_\odot$, have much smaller convective envelopes during their
pre-main-sequence phases and can suffer relatively larger metal enhancements. We have found that the disk lifetime is the most important parameter in determining the metallicity trend. Disk lifetimes $t_d > 10$ Myr can lead to significant metallicity increases for F stars that accrete planets.

2. The MS catalog of nearby F stars shows only marginal evidence for a trend of increasing metallicity with increasing stellar mass. Such a trend is consistent with the metallicity increases expected from the accretion of about 2 Jupiter-mass planets per star over a disk dispersal lifetime of 10 Myr. This work can only point out the possible existence of this trend. A more refined analysis using a larger sample of stars and/or more accurate metallicity determinations is required to definitely establish or rule out its existence.

Indeed, a great deal of follow-up work can be done to elucidate these concepts further. Because the predicted metallicity trends resulting from planetary accretion are fairly subtle, a larger and more complete sample of stars, with an increased mass range, is needed to obtain the statistics necessary for a firm conclusion. The trend is predicted to be most significant for stars in the mass range 1.5–2.5 $M_\odot$. It is also highly advantageous to obtain the stellar metallicities from spectroscopy, rather than the crude measure afforded by $uvby$ photometry. It is possible that an unforeseen effect is influencing the $b-y$ index as the spectral type changes. However, one additional complication is that metal lines are more difficult to observe for A stars. Another possible improvement is to recalibrate the Schuster & Nissen (1989) equation with recent spectroscopic metallicity estimates.

Notice that this approach—searching for metallicity trends in a wide sample of nearby stars—is complementary to directly studying the specific systems that are thought to have planets. The stars in these newly discovered planetary systems seem to be systematically high in metallicity (e.g., Gonzalez 1997a, 1997b). For small numbers of systems, however, it is difficult to separate the effects of metallicity enhancement from high initial metallicity. We note, for example, that planetary accretion does not account for the high metallicities of 55 Cnc and 51 Peg; these G stars should have large convection zones throughout the planet accretion phase of evolution. To circumvent the initial metallicity ambiguity, one can search for metallicity trends among F and G dwarfs in open clusters and binary systems. Wide binaries containing both an early G dwarf and an early F dwarf will thus provide another good test of this scenario.

Additional theoretical work also remains. A comprehensive set of pre-main-sequence evolutionary tracks should be computed with varying core and envelope metallicities, and an emphasis on the mass of the outer convection zone with time. Heavy elements settle out of stellar photospheres if given enough time, and these effects can also be included. Further refinements to the orbital migration problem should be done. Finally, the manner in which a giant planet spirals into a stellar photosphere should be studied in more detail.

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\textit{REFERENCES}

Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997 ApJ, 474, L113
Carlberg, A. G., Dawson, P. C., Hsu, T., & VandenBerg, D. A. 1985, ApJ, 294, 674
Edvardsson, B., Anderson, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
Forestini, M. 1994, A&A, 285, 473
Gonzalez, G. 1997a, MNRAS, 285, 403
———. 1997b, in ASP Conf. Ser. 000, Brown Dwarfs and Extrasolar Planets, ed. R. Rebolo (San Francisco: ASP), in press
Hauck, B., & Mermilliod, M. 1983, A&AS, 60, 61
Jeffery, C. S., Bailey, M. E., & Chambers, J. E. 1997, Observatory, 117, 224
Lin, D. N. C. 1997, in IAU Colloq. 163, Accretion Phenomena and Related Outflows, ed. L. Ferrario & D. Wickramasinghe, in press
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Fig. 3.—Same as Fig. 2, except that the minimum mixing mass beneath the stellar photosphere is $2M_\odot$.