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USING A *HIPPARCOS*-DERIVED HERTZSPRUNG-RUSSELL DIAGRAM TO LIMIT THE METALLICITY SCATTER OF STARS IN THE HYADES: ARE STARS POLLUTED?

A. C. Quillen[1,2]

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ABSTRACT

Hipparcos parallaxes and proper motions have made it possible to construct Hertzsprung-Russell (H-R) diagrams of nearby clusters with unprecedented accuracy. The standard deviation of high-fidelity, nonbinary, nonvariable stars about a model stellar evolution isochrone in the Hyades cluster is about 0.04 mag. We use this deviation to estimate an upper limit on the scatter in metallicities in stars in this cluster. From the gradient of the isochrone's evolution in the H-R diagram, we estimate an upper limit for the scatter of metallicities $\Delta[\mathrm{Fe/H}] \lesssim 0.03$ dex, a smaller limit than has previously been measured spectroscopically. This suggests that stars in open clusters are formed from gas that is nearly homogeneous in its metallicity. We consider the hypothesis that processes associated with planet formation can pollute the convection zone of stars. The low observed scatter about the isochrone in the Hyades suggests that pollution effects are not common and strong. If the position on the H-R diagram is insensitive to the metallicity of the convection zone and atmosphere, then stars that have very polluted convection zones can be identified from a comparison between their metallicity and position on the H-R diagram. Alternatively, if the pollution of the star by metals results in a large change in the position of the star on the H-R diagram in a direction perpendicular to the isochrone, then the low scatter of stars in the Hyades can be used to place constraints on quantity of high-Z material that could have polluted the stars.

Key words: open clusters and associations: individual (Hyades) — stars: abundances — stars: distances

1. INTRODUCTION

Both spectroscopic studies (e.g., Sneden et al. 1992; Armosky et al. 1994) and photometric studies (e.g., Suntzeff 1993; Folgheraiter, Penny, & Griffiths 1993; Heald et al. 1999; Da Costa & Armandroff 1990; Buonanno, Corsi, & Fusi Pecci 1981) have shown that the homogeneity of heavy-element abundances in globular clusters is quite small, typically less than 0.10 dex in [Fe/H]. The scatter of stars from model isochrones in Hertzsprung-Russell (H-R) diagrams derived from *Hubble Space Telescope* (*HST*) images in cases (such as NGC 6397) has been similar in size to the measurement errors, which implies that the metallicity variation among the stars in a given globular cluster must be less than a few hundredths of a dex (e.g., Piotto, Cool, & King 1997). Although high-quality H-R diagrams of coeval, low-metallicity, old globular clusters have been constructed, only quite recently has it been possible to construct H-R diagrams of comparable photometric quality (errors less than a few hundredths of a V-band magnitude) for younger and nearly solar-metallicity coeval systems such as open clusters (de Bruijne, Hoogerwerf, & de Zeeuw 2001).

Recent spectroscopic studies have established an as yet unexplained possible connection between the metallicity of a star and the existence of short-period extrasolar planets around the parent star (Gonzalez 1999; Santos, Israelian, & Mayor 2000; Gonzalez & Laws 2000; Gonzalez et al. 2001; Santos, Israelian, & Mayor 2001). Compared with stars in the solar neighborhood, parent stars of short-period extrasolar planets tend to have enhanced metallicities, $\Delta[\mathrm{Fe/H}] \approx 0.2 \pm 0.2$, compared with the Sun. However, there is a distribution in the observed metallicities; they range from about $[\mathrm{Fe/H}] \approx -0.4$ to $[\mathrm{Fe/H}] \approx 0.4$ (Gonzalez et al. 2001; Santos et al. 2001).

There are two possible explanations that account for the enhanced metallicities of parent stars with extrasolar planets. One possibility is that gaseous planets may be rarer around fairly low metallicity stars. Because the *HST* study of the globular cluster 47 Tuc ($[\mathrm{Fe/H}] = -0.7$) did not detect eclipses caused by planets, short-period Jovian planets could be an order of magnitude rarer than in the solar neighborhood (Gilliland et al. 2000). However, the lack of observed eclipses may instead be a result of the high stellar density in the cluster, which would have caused the disruption of planetary systems (Gilliland et al. 2000).

Alternatively, gaseous planets may be produced with equal frequency near stars spanning a range of metallicities, but the subsequent evolution of the planetary systems increases the metallicities of the parent stars. There is certainly evidence based on abundance analyses in our solar system that impacts from bodies in the asteroid belt or outer solar system have changed the surface abundances of Earth and the other planets (e.g., Morbidelli et al. 2000; Gautier et al. 2001). One consequence of the orbital migration of giant planets caused by scattering of a disk of planetesimals (Murray et al. 1998) is that the parent stars are polluted by star-impacting planetesimals (Quillen & Holman 2000). We infer that impacts with the Sun probably occurred more frequently and for more massive bodies during the early era of our solar system. The transfer of angular momentum via driving of density waves into a protoplanetary gaseous disk will cause the orbital migration of a planet, and it can also cause a planet to impact the star (see, e.g., Lin, Bodenheimer, & Richardson 1996; Trilling et al. 1998). One advantage of the orbital migration scenario involving ejec-

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[1] Department of Physics and Astronomy, University of Rochester, 600 Wilson Boulevard, Rochester, NY 14627-0171; aquillen@pas.rochester.edu.

[2] Visitor, Department of Physics, Technion, Israel Institute of Technology.

tion of planetesimals compared with that involving density waves driven into a gaseous disk is that it pollutes the stars with metal-rich planetary material when they are older and, so, have smaller convection zones (see, e.g., Laughlin & Adams 1997), allowing a smaller amount of metals to cause a larger surface metallicity enrichment.

Because the fraction of mass in the convection zone depends on the stellar mass, higher mass stars (e.g., F stars) with smaller convection zones could be more likely than lower mass stars with larger convection zones (e.g., K stars) to have enhanced metallicities resulting from pollution caused by planetary material. However, Pinsonneault, DePoy, & Coffee (2001) find no such trend among the parent stars of extrasolar planets. Santos et al. (2001) find that the distribution of metallicities for parent stars of extrasolar planets is inconsistent with a model in which these stars have been polluted by the addition of high-Z material.

Except for a narrow region at 6500 ± 300 K, known as the lithium dip, F stars keep lithium on their surface nearly their entire lifetime (see Balachandran 1995; Soderblom et al. 1993). The absence of Li depletion implies that the convection zone does not mix with the interior of the star except within the lithium dip. For F stars outside the lithium dip, little mixing takes place and a metallicity enhancement would last nearly the entire lifetime of the star; however, F stars within the dip would not be expected to show metallicity enhancements. Murray et al. (2001) and Murray & Chaboyer (2002) suggest that F stars near the lithium dip tend to have lower metallicities than F stars outside the lithium dip.

The stellar sample studied by Murray et al. (2001) and Murray & Chaboyer (2002) and surveyed for planets draws on the population of stars in the solar neighborhood and so spans a large range in ages and metallicities. To try to decouple the uncertainty caused by the metallicity scatter resulting from the range of stellar ages in the solar neighborhood from that caused by planet formation, we can examine the metallicity scatter in young clusters. We can assume that the stars in a given stellar cluster are the same age and were formed from gas that was fairly uniform in metallicity. Stars in the solar neighborhood are expected to have been born in a variety of environments, with about 10% born in OB associations, which then can become bound open clusters (Roberts 1957). The low-eccentricity orbits of the solar system planets require that the birth aggregate of the Sun was less than a few thousand stars (Adams & Laughlin 2001) and similar in size to the Trapezium cluster. Open clusters such as the Hyades, with about 400 known members, could have been as large as the Trapezium when younger.

Based on the study of Adams & Laughlin (2001), we expect that short-period extrasolar planets should have a high probability of surviving disruption from the passage of nearby stars in open clusters. Despite the fact that most stars in the solar neighborhood were formed in smaller, unbound groups, since planetary systems are likely to survive in open clusters we can use observations of the stars in open clusters to explore the possibility that significant stellar metallicity enhancements (pollution) are likely to occur after a star is formed. If metallicity enhancements occur, they would occur over a fairly short timescale, $\sim 10^6$ yr for the orbital migration scenario involving density waves in a gaseous disk (Trilling et al. 1998), and $\sim 10^7$ yr for the migration scenario involving scattering of planetesimals (Murray et al. 1998). In open clusters, planetary systems should survive long enough that they could have caused metallicity enhancements. Furthermore, nearby open clusters have nearly solar metallicities and so are a better match to the properties of parent stars of extrasolar planets than are the stars in globular clusters, which are comparatively extremely metal-poor.

It is difficult to envision any planet formation mechanism that would *not* cause differing amounts of metallicity pollution in different solar systems. We therefore expect a scatter in the metallicities in individual stars in any given stellar cluster and, so, a scatter in the H-R diagram about an isochrone. We might also expect a reduction in [C/Fe] because the inner solar system is deficient in light elements such as carbon. However, despite earlier reports, low values of [C/Fe] are not observed in the parent stars of the short-period extrasolar planets (Santos et al. 2001; Gonzalez et al. 2001). If ice-rich cometary material from the outer solar system is incorporated into the star on a later timescale, it is possible that light-element abundances could be restored. However, this could only occur if material from the outer solar system can survive evaporation. Evaporation rates are higher near the high-mass and more luminous stars; however, these stars, because of their lower mean densities, are also less likely to cause objects to fragment. Smaller sized bodies, because of their larger surface area, are less likely to achieve final impact, particularly after a series of close approaches, which can be caused by resonant trapping (Quillen & Holman 2000).

Spectroscopic studies of F stars in individual open clusters and moving groups have found that the metallicity scatter is small, $\Delta[\mathrm{Fe/H}] \lesssim 0.1$ (Boesgaard & Friel 1990; Friel & Boesgaard 1990, 1992). These authors also measured no measurable variation in the [C/Fe] ratio among all stars in all clusters studied. These studies would appear to rule out significant metallicity enhancement resulting from planet formation and subsequent planetary evolution in most stars. However, the number of F stars observed in each cluster in these studies was not more than a dozen. Establishing cluster membership is not always unambiguous, and so the samples of stars chosen for detailed spectroscopic study were not complete.

2. A LIMIT IN THE METALLICITY SCATTER FROM THE HYADES CLUSTER H-R DIAGRAM

Hipparcos parallaxes and proper motions have made it possible to construct H-R diagrams of nearby clusters with unprecedented accuracy (de Bruijne et al. 2001). With improved distances and a sample of 92 high-fidelity cluster stars, de Bruijne et al. have constructed an H-R diagram with estimated errors in the logarithm of the luminosity in solar units that average 0.030. The high-fidelity sample excludes members beyond 40 pc from the cluster center, multiple stars, variable stars, and stars with peculiar or uncertain parallaxes (see § 9.3 of de Bruijne et al. 2001). Stars were *not* excluded based on their position in the H-R diagram.

We show in Figure 1, as data points, the difference between the positions of the stars on the H-R diagram and the 630 Myr evolutionary track at $Z = 0.024$ interpolated from those given as tables by Girardi et al. (2000). The mean difference between the track and stars is not zero. This implies that the evolutionary track is not a perfect match to the H-R diagram of the cluster. It is impressive that the H-R

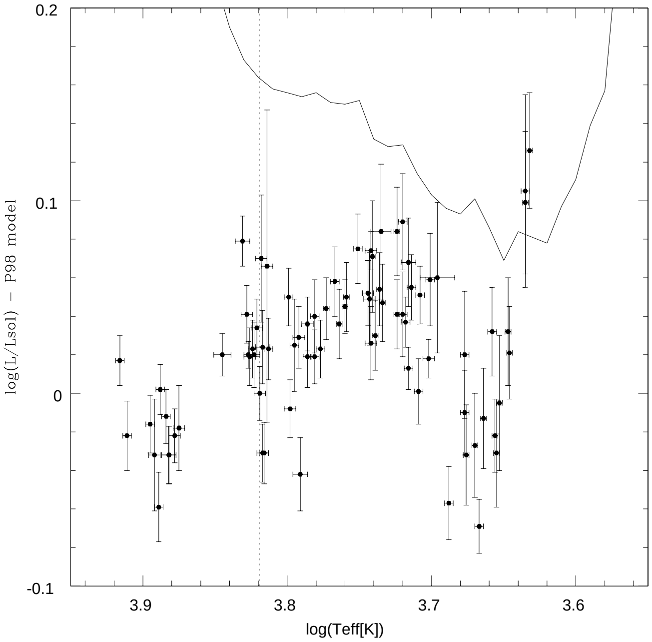

FIG. 1.—Difference between the 92 high-fidelity clusters Hyades stars identified by de Bruijne et al. (2001) and the $Z = 0.024$, 630 Myr evolutionary track of Girardi et al. (2000). We use temperatures and luminosities derived by de Bruijne et al. The scatter from the mean has a standard deviation of $\sigma = 0.04$ in the logarithm of the luminosity. *Solid line*, difference between coeval evolution tracks that differ by 0.1 dex in [Fe/H]; *dotted line*, position of the lithium dip in the Hyades.

diagram is so good that the evolutionary tracks (and associated bolometric corrections and color–to–effective temperature calibrations) can be tested to the level of 0.05 in the logarithm of the luminosity. Nevertheless, trends or smooth deviations from zero on this plot are not important for our study, since we are primarily interested in the scatter of the points. The age differences in the stars should be small compared with the age of the cluster, so other than observational errors, the variations in the stellar metallicities are the primary factor that would cause a scatter in the position of the points on the H-R diagram about the isochrone.

One can see from Figure 1 that the scatter off the evolutionary track is less than ~0.05 in the logarithm of the luminosity compared with the mean local value. However, an evolutionary track that differs by 0.1 dex in [Fe/H] (Fig. 1, *solid line*) is offset by about 0.15 in the logarithm of the luminosity. We therefore estimate that the star-to-star differences in metallicity could be only as large as 0.03 dex in [Fe/H]. This is only a bit larger than that estimated for the solar neighborhood by Murray et al. (2001), 0.02 dex, corresponding to 0.5 $M_\oplus$ of accreted iron from the inner solar system. This limit for the standard deviation of 0.03 dex in [Fe/H] is better than that previously estimated by Boesgaard & Friel (1990) from less than a dozen F stars, which was roughly 0.1 dex. This low level of scatter in the metallicities suggests that the gas from which the stars form is quite homogeneous in metallicity. Because massive stars become supernovae well before low-mass stars are finished accreting, this limit also suggests that nearby supernovae are not capable of substantially enriching the interstellar medium in their own nearby star-forming regions.

Stellar isochrones are computed assuming that stars do not accrete additional high-Z material after formation. Compared with a star that has not accreted additional material, where would we expect such a star to lie on the H-R diagram in the cluster? To know the answer to this question, we would need to calculate additional stellar evolutionary tracks from stellar models. While the properties of the radiative zone might be similar because it would have the same metallicity, and the energy transport through the convection should not be strongly affected by the opacity, the stellar atmosphere would be redder, and since this sets the boundary condition for the stellar model, we do not expect the star to lie at exactly the same position on the H-R diagram.

We consider two possibilities: (1) The position in the H-R diagram for a star that has accreted high-Z material is similar to that of one that has not. (2) There is a significant difference in the location on the H-R diagram and in a direction that would distance the star off the isochrone. If the first possibility is true, then we suggest that spectroscopic analyses can be used to identify candidate stars that have higher metallicities than would be expected from their positions on the H-R diagram. If such stars are found, it would provide strong evidence that they had been polluted by high-Z material after formation, and by processes associated with planet formation.

If the second possibility is likely, then we emphasize that the scatter from the isochrone observed in the H-R diagram can be used to constrain stellar pollution scenarios. Since the level of scatter has a standard deviation about 0.03 dex in [Fe/H], the average star could only have accreted about 0.7 $M_\oplus$ of accreted iron from the inner solar system.

Only a few stars remain outside the local mean in Figure 1 with deviations greater than 0.05 in the logarithm of the luminosity. However, stars with short-period giant planets are fairly common. In the solar neighborhood, 6%–8% of solar-type stars have short-period giant extrasolar planets (Mayor & Queloz 1995; Marcy, Cochran, & Mayor 2000). Of the 92 high-fidelity stars, we expect 6 ± 2 with significantly higher metallicities. None of the stars is sufficiently off the evolutionary track that an enhancement of 0.1–0.2 dex could be allowed. This would suggest that no star in the Hyades is likely to have a metallicity enhanced by the 30 $M_\oplus$ of rocky material needed to account for the enhanced metallicities of the parent stars of short-period extrasolar planets (Murray et al. 2001; Laughlin 2000; Murray & Chaboyer 2002), unless these stars happen to lie exactly on the same isochrone as their nonpolluted counterparts.

We have checked that there is no correlation between the magnitude of the scatter in the H-R diagram and the amount of lithium for the 19 F stars in the high-fidelity sample of de Bruijne et al. (2001) that have lithium abundances listed by Boesgaard (1987) or Thorburn et al. (1993). Even though the scatter in Figure 1 seems to peak near the lithium dip, the level of scatter does not seem to be obviously related to the mixing below the convection zone, as we would expect if it were correlated with the lithium abundance. We find no relation between the scatter off the isochrone and the effective temperature of the star, as would be expected from a pollution model that is sensitive to the percentage of mass within the convection zone.

3. DISCUSSION

In this paper, we have used the high-quality H-R diagram of the Hyades to place limits on the scatter in the metallicities of this cluster. We find that the scatter in [Fe/H] has a standard deviation of approximately 0.03 dex. This estimate is an improvement upon previous spectroscopic estimates and suggests that open clusters are formed from gas that is homogeneous in metallicity.

We have introduced the possibility that the extremely low scatter from a predicted isochrone can be used to constrain stellar pollution scenarios that involve the addition of high-Z material to the star from processes associated with planet formation. This can be done if stellar evolution tracks are calculated that include the addition of high-Z metals after formation to see where stars lie on the H-R diagram. If polluted stars lie off the isochrone for unpolluted stars, then the scatter of stars in the H-R diagram can be used to constrain the extent of stellar pollution. Otherwise, comparisons between spectroscopically measured metallicities and those estimated from the mean properties of the cluster can be used to identify stars that are likely to have been polluted by high-Z material.

Since few stars in young clusters have had comprehensive metallicity analyses, subsequent studies could be expanded and verified, also including more stars with a larger range of mass. Care should be taken that stars with discrepant metallicities are not thrown out of the sample and assumed to be non–cluster members. Currently there is no observational evidence that metallicities of different-mass stars in a given cluster differ. Comparison of spectroscopically measured metallicities in the Hyades, Pleiades, and NGC 2264 between G and F stars find that the metallicities are the same within the observational uncertainties (approximately 0.1 dex; King et al. 2000; Boesgaard & Friel 1990).

Despite the fact that the interstellar medium (along 1 kpc line-of-sight absorption lines) appears to have a uniform metallicity (Meyer, Jura, & Cardelli 1998), the metallicities of moving groups differ significantly (Boesgaard & Friel 1990; Friel & Boesgaard 1990), and the youngest ones seem to have increasingly subsolar values. There also are extremely metal-rich stars, some of which are not young. The high-metallicity stars are kinematically related; they tend to be in moving groups or streams (Soubiran 1999). This suggests that high-metallicity stars are formed in clusters that are uniform in metallicity, just like lower metallicity stars. This may rule out a scenario in which even a few percent of stars have their metallicity increased significantly by the effects of planetary processes and would instead support a model in which higher metallicity stars are more likely to harbor short-period planets. However, there is good evidence that one parent star of an extrasolar planet has engulfed planetary material: the detection of ^{6}Li in HD 82943 (Israelian et al. 2001; for evolutionary scenarios, see Sandquist et al. 2002). Further study of uniform populations such as are found in young clusters may be able to determine the relative statistical importance of each scenario.

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