Relation Between Stellar Metallicity and Debris Disks in the FEPS Sample

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The purpose of this document is to collate information, plots, and thoughts that are relevant to the production of a paper on this topic.

1. Introduction

What are debris disks? The short timescale for the removal of the dust in these systems indicates that it is non-primordial and is likely produced by recent collisions in a planetesimal disk.

Why debris disks are interesting:

The presence of debris may be a signature of the presence of a planetary system, either (1) because it indicates the presence of planetesimals, the building blocks of planets; (2) further the planetesimals may be stirred into eccentric orbits, which results in collisions, by the presence of either giant planets or embedded lower mass planets (Kenyon & Bromley).

Since the presence of giant planets may sculpt the resulting collisional debris, we may be able to use the debris to infer the underlying planetary architectures (e.g., Liou & Zook). This was one of the motivations for the FEPS project. Description of FEPS...

Debris disks might be connected to stellar metallicity: (1) because there is a well-established correlation between stellar metallicity and the presence of giant planets (Fischer & Valenti and references therein). (2) This correlation is interpreted as the result of the enhanced ability of a high metallicity disk to form planetesimals and giant planet cores within the lifetime of the gaseous disk, thereby enabling the formation of giant planets through core accretion. (3) Since high metallicity systems are therefore likely to produce both planetesimals and planets, those systems may also produce significant collisional debris.

In this paper we explore this possible connection.

2. Debris Disks Detected by FEPS

Include here a description of the FEPS sample (SpT, age, stellar metallicity). Also useful to describe FEPS sources in field vs. clusters (Pleiades, Hyades, etc.) if we keep section 4.4.

What instruments and bands are observed? What does an N-sigma excess mean? According to a discussion with Michael Meyer, we should stick with 3-σ excess a rough lower limit for a robust detection.

Figure 1 illustrates some of the characteristics of the FEPS sample, the distribution of the entire sample as a function of age and spectral type, and the same for the subset of sources with a detected infrared excesses at any of the wavelengths studied (3.6–160 μm). (This info is possibly useful to pare down the sample to be used for this study and to compare with the properties of the planet-bearing sample of stars. For example, we should probably exclude the primordial disks in Silverstone et al. 2005, as well as the spurious 70μm excess sources described by Serena in the telecon on 11/16/05. Should we also apply an age cut, e.g., at 3 Myr? 10 Myr?)

Compared to the planet-bearing stars, we cover a similar range of spectral types but much younger ages. So we are presumably studying some younger equivalents of these stars.

Describe sample statistics: number and fraction of entire sample with 24μm excesses, with 70μm excesses. (Refer to previous FEPS papers and some in preparation?) There are 328 sources in the FEPS sample, 323 of which have been observed so far (with MIPS). Of the sources observed, 72 have excesses reported in the FEPS database (as of 11/15/05) at $> 3\sigma$ at any FEPS wavelength.

Averaged over all ages, 22% of stars in the FEPS sample (72/328) have excesses 3σ or larger. Beyond 3 Myr, the incidence rate of excess does not vary strongly with age (surprising?). Characterize results for field vs. Pleiades, Hyades (if section 4.4 is kept).

(Figure 2: bar graphs of number of 3–5σ excesses at 24, 70, and 160μm.)

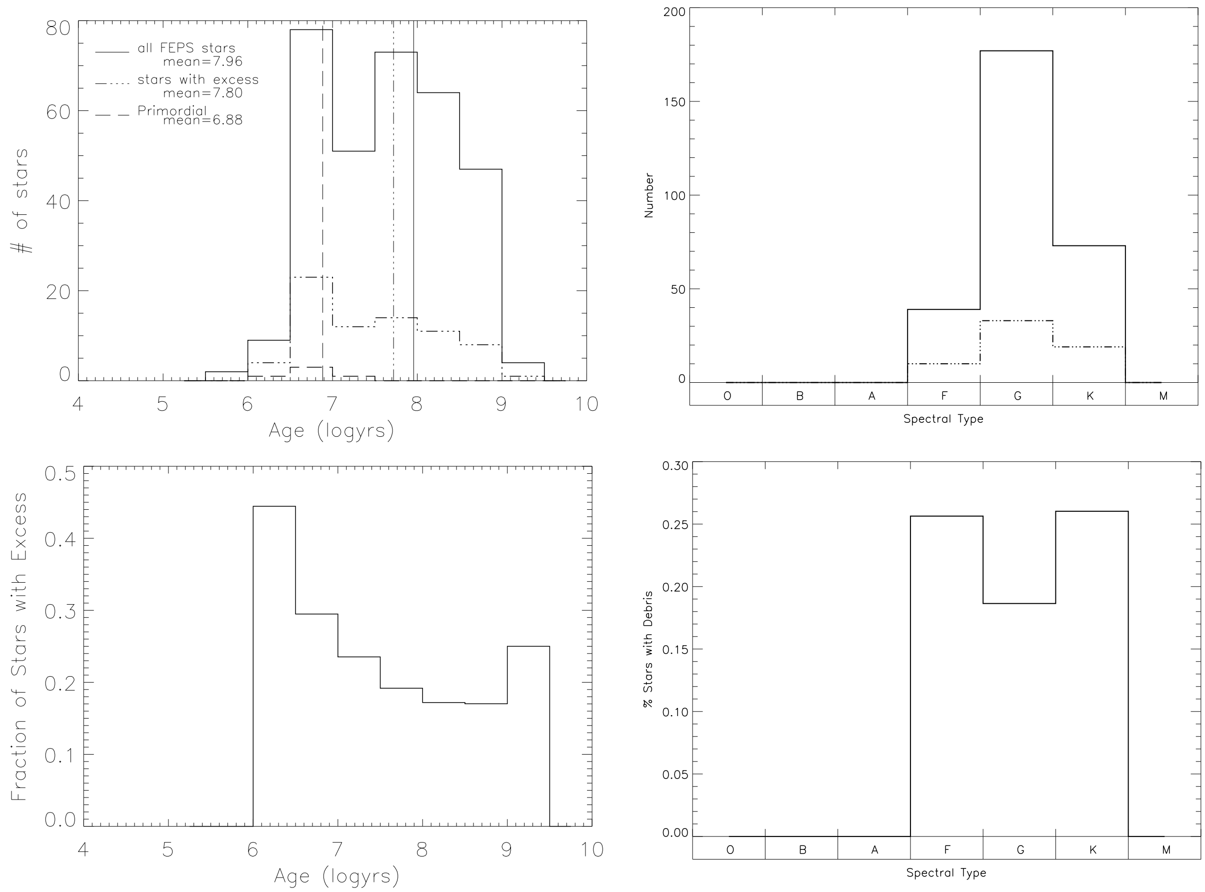

Fig. 1.— Plots characterizing the FEPS parent sample and the subset with IR excesses. Top Left: Histograms showing the distribution of FEPS sources as a function of age for the entire FEPS population (328 sources; solid line), FEPS sources with an excess $> 3\sigma$ (at any FEPS wavelength) as reported in the FEPS database as of early November 2005 (72 sources; dash-dot line); and the subset of excess sources that are likely to be primordial disks, as discussed in Silverstone et al. (5 sources; dashed line). The ages for the sources were obtained from Lynne Hillenbrand's website (http://www.astro.caltech.edu/∼lah/feps/ages/ages.out.format). The mean of each distribution is plotted as the vertical line in the same linestyle as the distribution, and it is also listed in the legend. Bottom Left: The same information plotted as the fraction of FEPS sources with an excess $> 3\sigma$ as a function of age. *It would be useful to include error bars on this.* Top Right: Histograms showing the distribution of FEPS sources as a function of stellar spectral type for the all FEPS sources with spectral types in the FEPS database (289 sources; solid line) and the subset of these sources with an excess $> 3\sigma$ (at any MIPS wavelength) as reported in the FEPS database as of early November 2005 (dash-dot line). *Probably best to agree on what λ excesses to plot.* Bottom Right: The same information plotted as a fraction of FEPS sources with an excess $> 3\sigma$ as a function of age.

Fig. 2.—

3. Stellar Metallicity Measurements

There are many stellar metallicity measurements in the literature for the FEPS sources. Depending on what is assumed in the studies, there could be different systematics associated with each study. E.g., for spectroscopic metallicities, the derived metallicities would depend on the gf values used, the accuracy with which the stellar atmosphere parameters were derived, the model atmospheres used, etc.

Since our goal is to infer trends in the incidence rate of debris vs. stellar metallicity, our approach has been to select measurements from the literature that were carried out systematically for large samples. The hope is that the systematics would be common to all stars in the sample and that trends could be robustly inferred. If we can calibrate the samples against each other, we would combine the samples.

3.1. Spectroscopy

Stellar metallicities have been measured spectroscopically by Valenti & Fischer (2005) for a sample of 1040 nearby stars that are currently being monitored for the presence of extrasolar planets. 85 of the FEPS targets have stellar metallicities measured in this study. 83 have been observed so far as part of FEPS.

How does this technique work? What are the uncertainties or systematics? How accurate are the metallicities?

Figure 3 compares the stellar metallicity distribution for all FEPS sources with metallicities from Valenti & Fischer with the subset of these which have a detected MIPS excess at the 3-σ, 4-σ, or 5-σ level. The 3- and 4-σ distributions have similar means to the parent sample, although the distribution of sources with excess is a flatter than the parent sample (i.e., has larger width).

Discuss the range in age and SpT of the sources measured with this technique compared to FEPS as a whole.

3.2. Stromgren Photometry

Stellar metallicities have also been measured using Stromgren photometry by Nordstrom et al. (2004) for a sample of nearby stars. 153 of the FEPS targets have stellar metallicities measured in this study. 149 have been observed so far as part of FEPS.

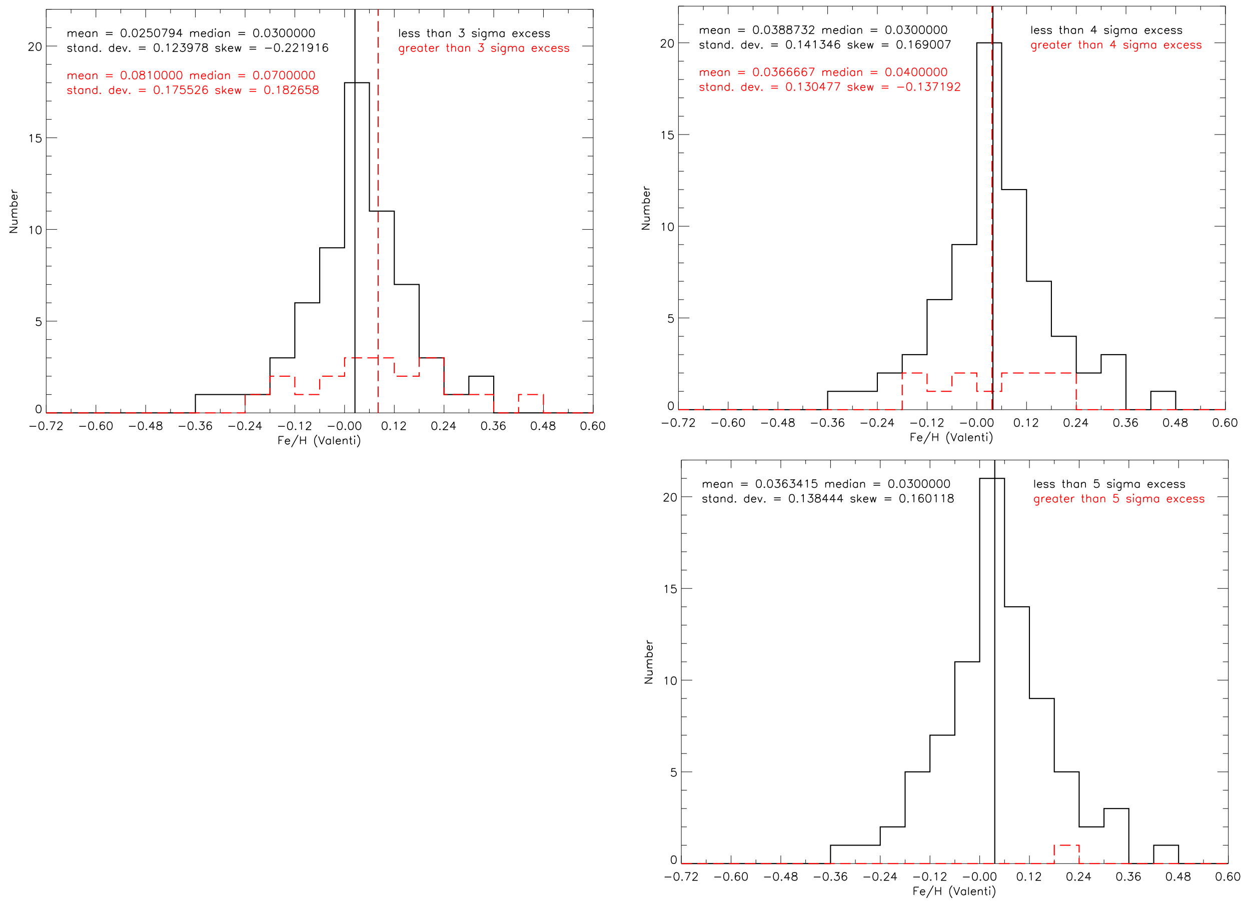

Fig. 3.— Histograms of stellar metallicity derived from high resolution spectroscopy (Valenti & Fischer 2005) for sources in the FEPS database. Only sources that have been observed with MIPS to date (323 sources) are included. The red histograms indicate sources with an N-σ (3-σ upper left; 4-σ upper right; 5-σ lower right) or greater excess at 24, 70, or 160 μm as detected by MIPS. The black histograms indicates sources lacking an excess at 24, 70, or 160μm at the Nσ level. The red and black vertical lines indicate the mean of the distribution of sources with and without excesses respectively. Other basic statistics for each distribution are given in the top left-hand corner of the plot.

How does this technique work? What are the uncertainties or systematics? How accurate are the metallicities?

Figure 4 compares the stellar metallicity distribution for all FEPS sources with metallicities from Nordstrom et al. with the subset of these which have a detected MIPS excess at the 3-, 4-, or 5-σ level. The result is similar to that found for the Valenti & Fischer sample; the shape of the distributions and the means are similar for samples with and without IR excesses.

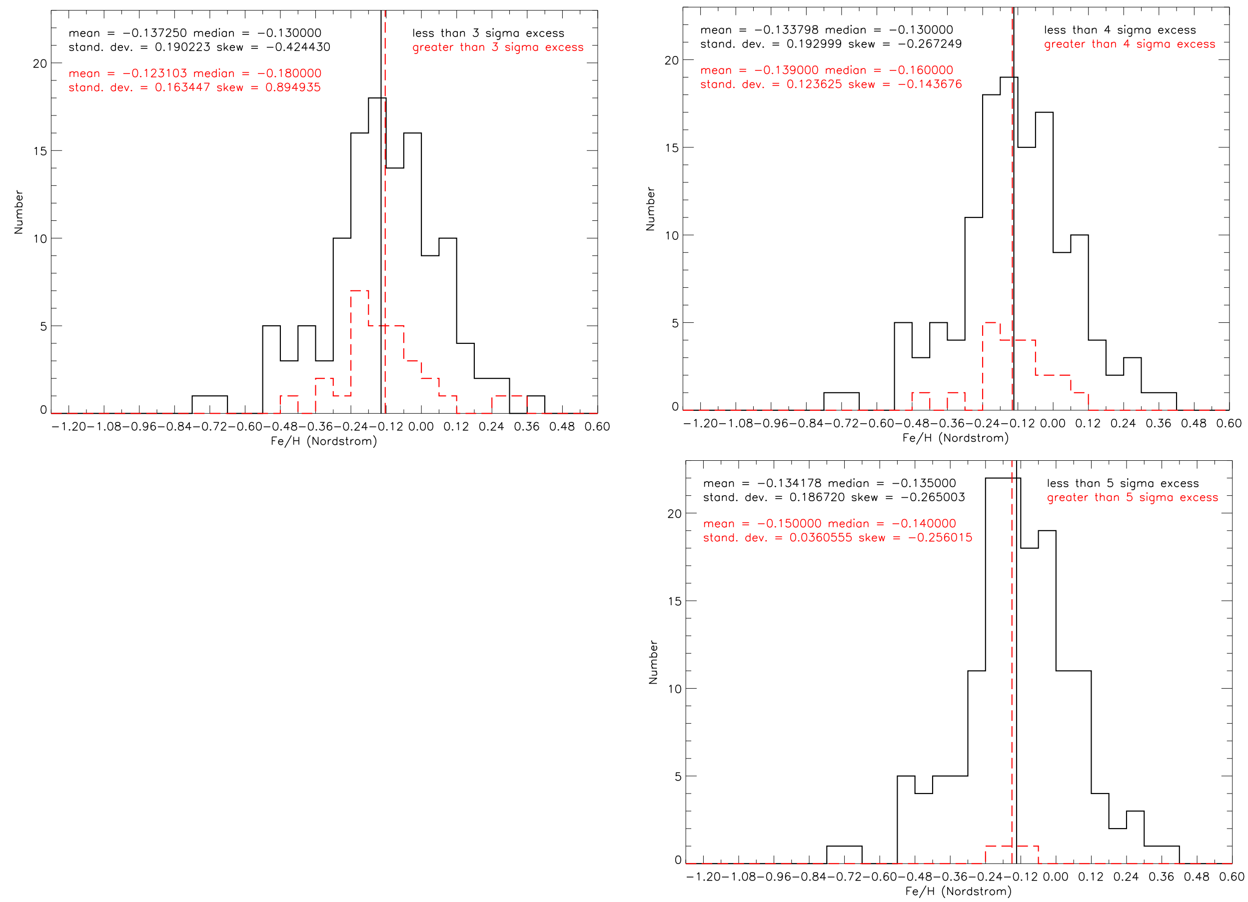

Fig. 4.— Histograms of stellar metallicity as determined from Stromgren photometry (Nordstrom et al. 2004) for sources in the FEPS database. Only sources that have been observed by MIPS to date were included in the histogram (323 sources). The red histograms indicate sources with an N-σ (3-σ upper left; 4-σ upper right; 5-σ lower right) or greater excess at 24, 70, or 160 μm as detected by MIPS. The black histograms indicates sources lacking an excess at 24, 70, or 160 μm at the Nσ level. The red and black vertical lines indicate the mean of the distribution of sources with and without excesses respectively. Other basic statistics for each distribution are given in the top left-hand corner of the plot.

Discuss the range in age and SpT for the sources measured with this technique compared to FEPS overall.

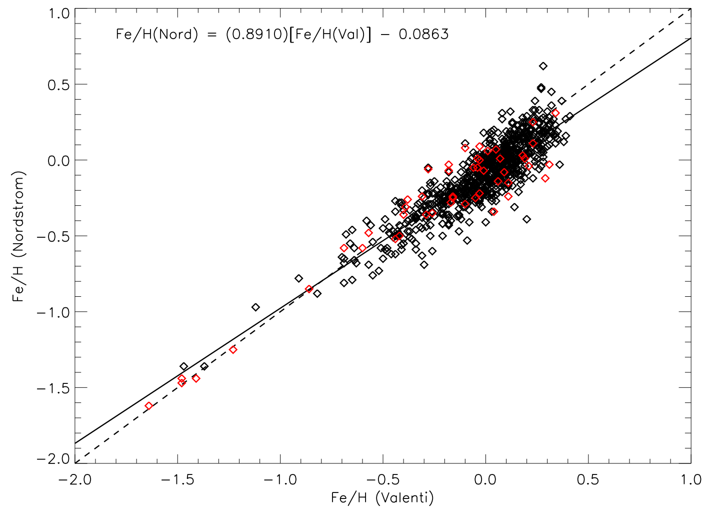

Fig. 5.— Metallicities reported by the Nordstrom study compared with the metallicity reported by the Valenti study for the sources in common to the two studies (black points). (This sample includes sources outside the FEPS sample.) The red diamonds indicate those stars that are 300 Myr old or younger, as identified by the Valenti study. (These points were identified at the request of Steve Strom. The similarity between the distributions of the red and black points shows that microturbulance in young stars does not compromise the metallicity measurements from Stromgren photometry.) The dashed line corresponds to a line with a slope of one and a y-intercept of zero. The Nordstrom metallicities appear to be are biased by ∼0.1 dex toward smaller metallicities compared to the Valenti measurements. This agrees well with the metallicities shown in Figures 3 (Valenti) and Figures 4 (Nordstrom). The dotted line shows a fit to "spectroscopic metallicity" as a function of "photometric metallicity".

3.3. Comparison of Stellar Metallicities from Spectroscopy and Stromgren Photometry

The metallicity studies of Valenti & Fischer and Nordstrom et al. have 803 sources in common. By comparing the measurements for these sources we can derive a mean relation between the metallicities measured with the two techniques. Figure 5 shows this comparison. The Nordstrom et al. metallicities were calibrated to the Valenti & Fischer scale using a linear least squares fit:

$$\mathrm{Fe/H(Valenti)} = 1.1224[\mathrm{Fe/H(Nordstrom)}] + 0.0969.$$

Using this relation to convert "photometric metallicities" into equivalent "spectroscopic metallicities", we can combine the metallicities measured with the two different techniques. Figure 6 (upper and lower left, lower right) shows the result of this. These plots are slightly different from Figures 3 and 4. They compare the stellar metallicity distribution of excess sources against the distribution for the FEPS sample with metallicities, rather than the distributions above and below an $N\sigma$ cut. Again, there is no strong correlation of the incidence of IR excess with stellar metallicity.

We can investigate more sophisticated ways in which to compare the combine the samples (e.g., Martell and Laughlin).

4. Results

The lack of an obvious correlation between stellar metallicity and collisional debris stands in contrast to the observed correlation between stellar metallicity and presence of giant planets. Figure 6 shows the metallicity distribution for stars with extrasolar giant planets detected by precision radial velocities (upper right; Fischer & Valenti) and FEPS sources with debris (other plots; previous section) compared to the stellar metallicity distributions for their parent samples. The parent samples cover the same range of stellar metallicity.

[Do FEPS and PRV samples have similar distributions in SpT? They do sample different ages.]

For fun, we can examine the ratio of the histograms in Figure 6a, the incidence rate of IR excess as a function of stellar metallicity. This is shown in Figure 7. Discuss errorbars. The ratio is flat (or decreasing) with metallicity over the range [Fe/H]=-0.5 to 0.2. There is a hint of an increase in the incidence rate of excess at higher metallicity. However, the error bars here are large due to the small sample of higher metallicity stars in the sample. A conservative approach would be to say that there is no obvious correlation with metallicity, certainly not at the level that is seen for the incidence rate of giant planets as a function of metallicity.

The lack of a strong correlation between stellar metallicity and the presence of collisional debris may arise from the potentially larger number of factors that influence debris production compared to giant planet formation. These processes are described below.

4.1. Processes Influencing Stellar Metallicity

The metallicity of a star is likely to be influenced by several factors. Probably of primary importance is the metallicity of the cloud from which the star formed. If the cloud material accretes onto the star via a circumstellar disk (as is expected in the current paradigm of star formation) and the gas and dust accrete equally onto the star, the stellar metallicity would

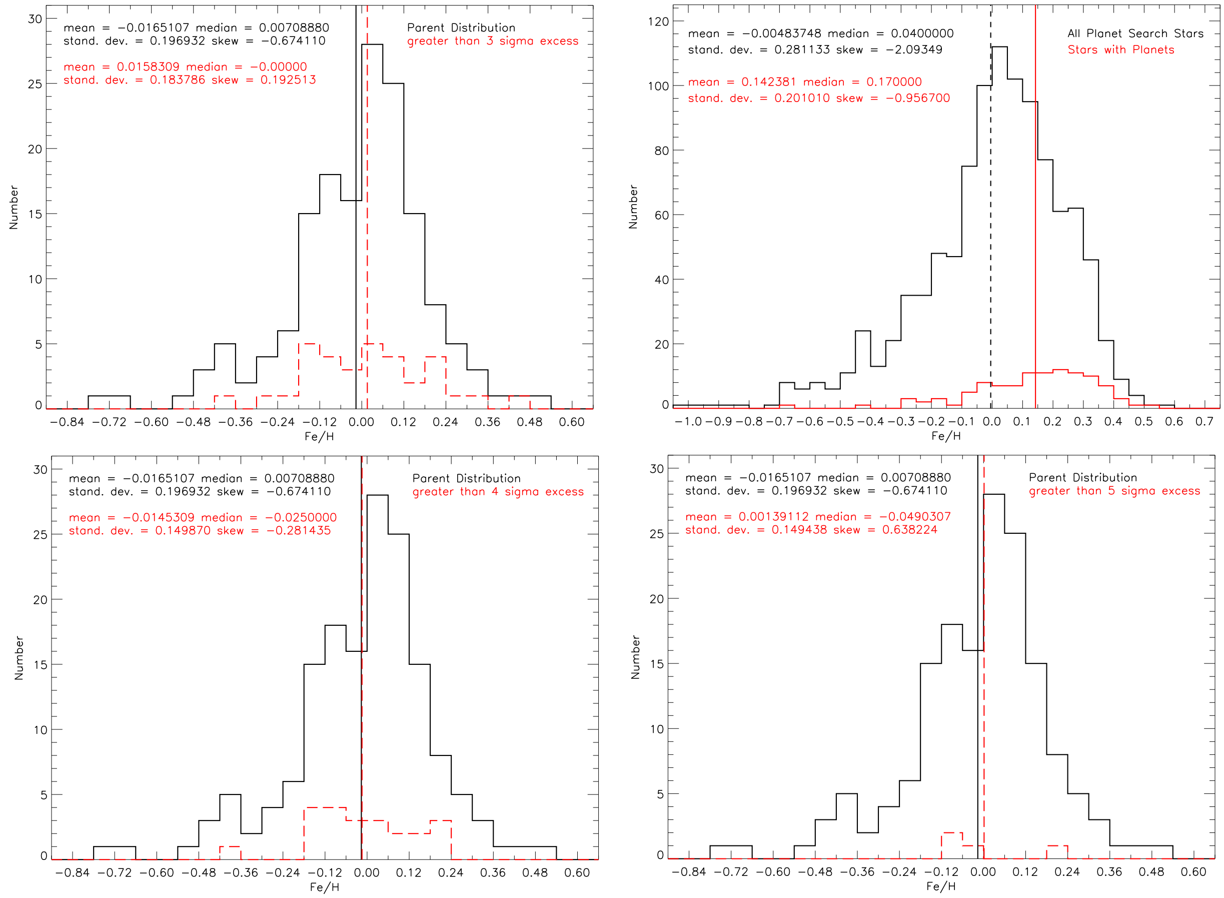

Fig. 6.— Upper right: Histogram of stellar metallicity for all stars in the Keck, Lick, and AAT planet search programs (black) compared with the distribution for the subset of stars with detected planets Fischer & Valenti (2005; red). Other plots: Histogram of metallicities computed from the Nordstrom study (adjusted to Valenti scale) combined with those from Valenti & Fischer (in black; 159 sources). The distributions of metallicities for the subset of sources with an IR excess at the 3σ level (upper left), 4σ level (lower left) and 5σ level (lower right) are plotted in red. The black dashed lines in all plots indicate the mean of the distribution for the parent sample the red solid line indicates the mean of the distribution for the sources with debris or planets. There is a larger offset in mean metallicity between those stars with planets and those without planets than there is between stars with debris disks and those without debris disks.

reflect the cloud metallicity.

In contrast, if planetesimals and planets form in the disk and are not accreted by the star, the metallicity of the star would be reduced relative to the cloud (Wilden et al. 2002) The magnitude of this effect can be significant but is unlikely to dominate. The metallicity variation among G and K stars in the Pleiades is ± 0.05 dex; this is equivalent to the most metal-rich stars having accreted $\sim 300 M_{\oplus}$ more metals than the most metal-poor stars, an

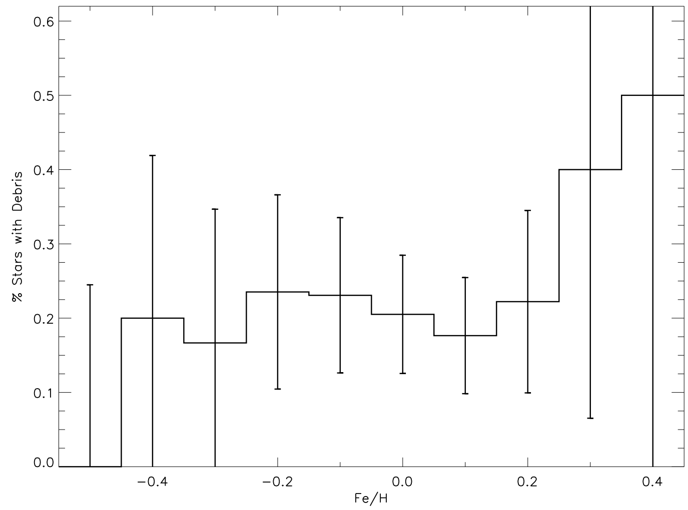

Fig. 7.— Incidence rate of IR excess ($> 3\sigma$ at a MIPS wavelength) as a function of stellar metallicity for the FEPS sample. There is a hint of a higher incidence rate of IR excess at the highest stellar metallicities. But larger samples are needed to establish this.

amount that is 2–5 times the heavy elements contained in the planets in the solar system (Wilden et al. 2002). A disk that underwent core accretion, forming many planetesimals or ice giants but no gas giant planets, would have a similar impact on the stellar metallicity.

The reduction in metallicity is measurable, but small compared to the span of metallicity among the field stars.

At later times, the metallicity of the star may be influenced by the accretion of solids in the form of planets, planetesimals, or small dust. See the discussion in Fischer & Valenti and Wilden limiting the role of these effects. To this we can add that most of the debris disks studied to date show inner holes, implying that very little mass in small grains reaches the star, e.g., as a consequence of PR drag (Jura et al. 2004; Chen et al. in prep). This is presumably the result of grain destruction via collisions which limits the radial migration of grains; it should dominate preferentially at early times when debris disks are more massive (Dominik & Decin; Kenyon & Bromley; Wyatt 2004). More pollution is expected at later times, or in lower mass disks. What might be expected for FEPS given its age range?

4.2. Factors Influencing Giant Planet Formation

The efficiency of giant planet formation via core accretion is expected to depend sensitively on the total solid surface density in the disk (REF), a condition which greatly favors the production of giant planets in disks with either larger masses and/or higher metallicities. In comparison, giant planet formation via gravitational instabilities depends on the mass of the disk relative to the star; the efficiency of this planet formation pathway may be more neutral with respect to the disk metallicity compared to core accretion. There might be some anti-correlation with disk metallicity if a higher disk metallicity restricts the ability of the disk to cool, inhibiting the formation of protoplanetary condensations (Nelson, PPV) and/or inducing more rapid inward migration (Boss, PPV).

The mode of giant planet formation also has an impact on the stellar metallicity, with core accretion withholding more solids from the star and decreasing the metallicity of the star. Since giant planet formation via gravitational instability does not segregate the gas from the solids in the disk, it should produce little change in the metallicity of the star relative to the disk.

Thus, one might expect that in clusters the most metal rich stars either have no planets or those that formed via gravitational instability; we could test this when there are more detections of planets in clusters.

Apart from this differential effect in clusters, we would expect that systems that have formed planets via gravitational instability would not be biased toward high metallicity (either because of initial conditions or because of the segregation of solids). Interestingly, the systems with the most robustly defined eccentric planetary systems (70 Vir and 16 Cyg b) are not particularly metal rich (Fe/H = -0.01 and 0.04, respectively) and are close to the mean of the parent sample for PRV searches for planets. 70 Vir is also massive ($M_p = 7.44 M_J$). Of of the planets detected by PRV, these systems are among the more likely to have formed via gravitational instability.

4.3. Processes Influencing Collisional Debris

The above discussion has raised several factors that also influence the production of collisional debris. As a starting point, both higher initial disk metallicity and higher disk mass favor the production of planetesimals as an initial step in core accretion. However, these same conditions *strongly* favor the production of massive giant planetary cores through the agglomeration of planetesimals, so perhaps the residual population of planetesimals (following giant planet formation) is not a strong function of either initial disk metallicity or mass.

Once planetesimals have formed, collisions between planetesimals will lead to the production of debris at a rate that depends on the mass of the planetesimal population and the extent to which they are stirred (i.e., their eccentricities and inclinations). Stirring mechanisms include large ($\sim$ 1000 km) embedded protoplanets (Kenyon & Bromley) and interactions with giant planets in the same system (REF).

The formation of embedded protoplanets is expected to begin at small radii and propagate outward, inducing an outwardly propagating wave of debris production. This results in a rapid collisional grinding of the planetesimal disk, producing a mass in debris that declines inversely with time (Dominik & Decin). This slope is consistent with the upper envelope of the mass in small grains measured for debris disks detected at submillimeter wavelengths (Wyatt?; Liu et al. 2004; Najita & Williams 2005). At late times, the rate of debris production is expected to decline more steeply, as t^{-2}, as PR drag takes over from collisions as the dominant grain destruction mechanism (Dominik & Decin).

When giant planets are present, an even greater range of evolutionary histories is possible. An interesting counterpoint is the scenario that has been proposed to explain the late heavy bombardment phase of our own solar system. (Some more detailed description.) All is quiet for some 800 Myr, with planetesimals in the Kuiper Belt colliding and inducing the migration of the giant planets (Hahn & Malhotra). As Jupiter and Saturn come into a 2:1 resonance, their orbits become more highly eccentric (What is the maximum eccentricity?), inducing higher eccentricity in the Kuiper and asteroid Belts. In a period of 10s of Myr, some 90% of asteroids and KBOs are scattered into collisions with inner solar system bodies or are ejected from the system (Strom et al. 2005; Morbidelli, Levison, Gomes). Thus, the evolutionary histories of planetesimal disks can depend sensitively on the architectures of giant planetary systems.

Such stochastic LHB events contrast starkly with the steady grinding expected for planetesimal systems without giant planets. There is some observational evidence that such processes play a role in determining the properties of debris disks. Stochasticity is suggested by the strengths of 24μm excesses associated with nearby A stars as a function of age (Rieke et al. 2005). In addition, the average grain orbital radius for debris disks detected in the submillimeter shows no correlation with age, suggesting that processes beyond self-stirring play a significant role in the collisional evolution of planetesimal disks (Najita & Williams 2005).

To summarize, the amount of debris that is present in a given system depends on multiple factors beyond the initial metallicity of the disk. Giant planet formation can have a major impact, both in restricting the total mass that is left as planetesimals and in affecting the degree of stirring and collisional grinding of a planetesimal disk. Since these effects go in opposite directions (the presence of giant planets could either decrease or increase the rate of debris production), we might expect debris production not to be strongly correlated with conditions favoring giant planets, i.e., with high stellar metallicity. This is in fact what is observed.

4.4. Results for Clusters

(Pleiades, Hyades.)

Thinking back to the discussion in section 4.1 about how the formation and retention of planetesimals and giant planet cores can effectively reduce the metallicity of the star relative to the cloud, it seems that clusters are great laboratories in which to explore this effect because they presumably control for the initial conditions (all stars formed from material with the same metallicity) and allow one to explore the diversity of results that might be produced by other factors. Thus the range of stellar metallicities in clusters can be a measure of the diversity of outcomes of the planet/planetesimal formation process (D. Lin, personal communication).

Since the likelihood of forming giant planets is a sensitive function of the total solid surface density in the disk, the diversity in stellar metallicity within a cluster might arise as a result of a range of disk masses. Going one step further, the most metal-poor stars in a cluster are then those most likely to have formed planetary systems or massive planetesimal disks via core accretion. Can we learn anything about this from the clusters in the FEPS sample?

Hyades: is at the age of LHB in our solar system, is more metal-rich than the sun. Naively, it might have more planets and more debris disks.

Has few planets discovered so far (Laughlin: should find 7 at its metallicity given FV, instead find 0 or 1?). Has few debris disks discovered so far. Cieza, Paulson, and Cochran (poster at PPV; FEPS + GO data) find 0/51 excesses at 24μm and 3/51 at 70μm or 4%).

Why is this? In the harsher radiation environment of the Hyades in its youth (Laughlin: more extreme than the Trapezium; REF?), gaseous disks probably dissipated more rapidly via photoevaporation, stunting the growth of giant planets. So despite the higher metallicity, we shouldn't expect to find a lot of planets in the Hyades.

OK, but if planetesimal formation goes much quicker than giant planet formation, the planetesimals and protoplanets that didn't grow into giant planets could still be left behind. These might be quiescent if there aren't enough giant planets or plutos to stir them into collisions. Or they might dissipate early on as stellar flybys, expected to be more numerous in a dense cluster environment eject KBOs and induce greater eccentricity in the planetesimal population (Sedna: Brown; recent Kenyon & Bromley paper). The stellar metallicity spread in the Hyades is a constraint on how much solids could have been left behind as planetesimals or protoplanets. It isn't very large.

Pleiades: at 100 Myr, has 10% incidence rate of debris disks for solar-masss Pleiads from FEPS (2-3/20 stars; Stauffer et al. 2005). Similar incidence rate for the Pleiades from Gorlova/MIPS. This is about half the incidence rate of excess for FEPS overall (72/328=22%). Pleiades has similarly small spread in stellar metallicity (Wilden et al. 2002)

4.5. Comparison with Other Results

Bryden et al. (2005) found no obvious correlation of debris with metallicity for sample of 7 stars with detected debris based on a parent sample of 69 FGK main-sequence field stars (their Fig. 3). Parent sample chosen indenpendent of age, metallicity, or previously known IR excess. Median age $\sim$4 Gyr.

Greaves et al. (2005b) anti-correlation between metallicity and debris based on sub-mm detections. Tau Ceti is and example of a low metallicity star with a submm detection.

Bryden sample includes 11 stars with known planets. Only 1 has an IR excess, a detection rate similar to that for the rest of the stars in the sample (i.e., without planets). That star is 70 Vir! which is amazing because it is highly eccentric. So much for that idea. It (and all the other planets in the Beichman sample) have Neptune-like planets?

Beichman finds correlation between debris and planets based on detection of debris is 6/26 planet-bearing stars, a higher fraction than average for stars of that SpT and age. Amazingly, the detected systems have large eccentricities and masses. Shows diversity of debris vs. planets since systems with similar orbital parameters can have varying amounts of excess. Stars with excess and planets have slightly lower mean metallicity than stars planets but no excess. Concludes that there is no evidence for higher metallicity stars associated with more dust.

Our results are similar, based on a larger sample, selected in a different way.

Beichman results are for weaker excesses than those required for detection in the submm. At that level of excess, there's no correlation between planets and excess (Greaves et al. 2004).

5. Meta-discussion: Initial Conditions and Evolutionary Sequence

A Strom-ian topic.

Evolutionary scenario is similar to ideas in Bryden et al. 2005.

The LHB scenario of Morbidelli et al. shows how giant planets on eccentric orbits can eject planetesimals while also generating debris, significantly reducing the mass of the planetesimal belt in a short span of time. Generalizing this scenario, one might expect that systems that form giant planets that are initially eccentric might eject most of the planetesimals from the system early on, producing little collisional debris at later times. But then there are systems like 70 Vir.

Thanks to Greg Laughlin and Doug Lin for useful conversations and helpful insight on this topic.