

**SPITZER OBSERVATIONS OF THE HYADES: CIRCUMSTELLAR DEBRIS DISKS AT 625 Myr OF AGE**

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Received 2007 November 12; accepted 2008 January 25

**ABSTRACT**

We use the *Spitzer Space Telescope* to search for infrared excess at 24, 70, and 160 μm due to debris disks around a sample of 45 FGK-type members of the Hyades. We supplement our observations with archival 24 and 70 μm *Spitzer* data of an additional 22 FGK-type and 11 A-type Hyades members in order to provide robust statistics on the incidence of debris disks at 625 Myr of age, an era corresponding to the late heavy bombardment in the solar system. We find that none of the 67 FGK-type stars in our sample show evidence for a debris disk, while 2 out of the 11 A-type stars do. This difference in debris disk detection rate is likely to be due to a sensitivity bias in favor of early-type stars. The fractional disk luminosity, \(L_{\text{dust}}/L_\star\), of the disks around the two A-type stars is \(~4 \times 10^{-5}\), a level that is below the sensitivity of our observations toward the FGK-type stars. However, our sensitivity limits for FGK-type stars are able to exclude, at the 2 \(\sigma\) level, frequencies higher than 12% and 5% of disks with \(L_{\text{dust}}/L_\star > 1 \times 10^{-4}\) and \(L_{\text{dust}}/L_\star > 5 \times 10^{-4}\), respectively. We also use our sensitivity limits and debris disk models to constrain the maximum mass of dust, as a function of distance from the stars, that could remain undetected around our targets.

*Subject headings: *circumstellar matter — open clusters and associations: individual (Hyades)*

**Online material:** color figures, machine-readable tables

1. INTRODUCTION

Soon after *IRAS* discovered cold circumstellar disks around main-sequence (MS) stars (Aumann et al. 1984), it was realized that these disks could not be made of primordial material. Follow-up CO observations (e.g., Yamashita et al. 1993) showed that molecular gas was highly depleted around these disks. Since, in the absence of gas, the survival time of dust due to dissipation processes such as radiation/wind pressure and the Poynting-Robertson effect is much shorter than the ages of MS stars, these systems are believed to be debris disks where dust is continuously replenished by collisions between planetesimals, the building blocks of planets. Because of their probable connection with the formation of planetary systems, debris disks rapidly became the subject of many studies. However, *IRAS* was only sensitive enough to study bright nearby objects, and most of the pre-*Spitzer* statistics come from surveys performed by *IRAS*’s successor, the *Infrared Space Observatory* (ISO). Hабин et al. (2001) studied 84 nearby \((d < 25\text{ pc})\) A, F, G, and K stars for which ISO was sensitive to photospheric fluxes and detected 60 μm excess in \(\sim50\%\) of the stars younger than 400 Myr and in 10% of the stars older than 400 Myr. They suggest that this sudden decrease in the fraction of stars with disks around 400 Myr is related to the lifetime of planetesimals that replenish the dust. Spangler et al. (2001) observed \(\sim 150\) pre-MS and young MS stars and detected 60 μm excess in \(\sim25\%\) of the objects. Their observations do not confirm a sudden decrease in the disk fraction around 400 Myr but rather suggest a power-law relationship (index approximately \(-2\)) between the age of the star and the fractional dust luminosity, \(L_{\text{dust}}/L_\star\). They argue that such a power law naturally arises in collisionally replenished debris disks. The discrepancies in the results from these ISO surveys can probably be traced back to the different target selection criteria and observing strategies and to small number statistics. However, since conclusions from Háböck et al. (2001) and Spangler et al. (2001) were not totally consistent, ISO was unable to provide a clear picture for the evolution of debris disks.

Fortunately, *Spitzer*’s unprecedented sensitivity has recently allowed many studies of large samples of pre-MS and MS stars in the mid- and far-IR. These studies are rapidly providing important clues on the evolution of debris disks. Rieke et al. (2005) studied over 250 A-type stars and concluded that, even though the incidence of 24 μm excess clearly decreases with increasing stellar age, a very large dispersion on the magnitude of the IR excesses is seen at every age. Su et al. (2006) find that A-type stars show a similar qualitative behavior at 70 μm. However, at this wavelength, the IR excess declines more slowly with time than at 24 μm. The decay timescale is estimated to be \(\sim 150\text{ Myr}\) for the 24 μm excess and \(\sim 850\text{ Myr}\) for the 70 μm excess. Trilling et al. (2008) studied field FGK-type stars and found that \(\sim 4\%\) and \(\sim 16\%\) of them show detectable IR excesses at 24 and 70 μm, respectively. These disk frequencies are roughly a factor of 2 lower than those found for A-type stars at the same wavelengths. They also found that solar-type stars have an almost constant disk frequency beyond 1 Gyr; hence, they concluded that their debris disk decay timescale is significantly larger than that for an A-type star. Gautier et al. (2007) studied a sample of nearby M-type stars but detected no significant far-IR excesses. However, given the sensitivity of their survey, they concluded that the average Multi-band Imaging Photometer for *Spitzer* (MIPS) excesses, measured in photospheric flux units, of the M-type stars are at least a factor of 4 lower than those of solar-type stars.

The *Spitzer* study of the Hyades presented in this paper is intended to provide additional clues by giving robust statistics on the frequency of debris disks at 625 Myr of age for a homogeneous sample of MS stars. At 46 pc, the Hyades is the nearest star cluster to the Sun and represents a sample of stars formed at the same epoch with the same heavy-element abundance ([Fe/H] = 0.13 \(\pm\) 0.01; Paulson et al. 2003).

The 625 Myr age of the Hyades places it at an extremely interesting era in the evolution of planetary systems. This age corresponds almost exactly to the era of the late heavy bombardment...
(LHB) in our solar system, about 3.9 Gyr ago (Tera et al. 1973). The cratering record of the Moon, Mars, and Mercury all indicate that the inner planets experienced intense bombardment by large bodies at that time. There is still intense debate as to whether the LHB represented merely the end of an exponential decrease in the impact rate from the formation of the terrestrial planets (Wetherill 1975, 1977; Neukum & Ivanov 1994) or was instead a short, intense spike in the bombardment rate when the solar system was about 600 Myr old (Ryder 1990; Cohen 2002). In either case, the LHB of our solar system clearly indicates that at an age of ~600 Myr there was still a major debris disk present that was undergoing rapid evolution. Large, asteroid-size bodies had been built up during the early planet-building era, but not all of these bodies had been incorporated into the planets. At the time of the LHB, these bodies were undergoing an era of significant collisions with the inner planets, and presumably with each other as well. These collisions would have generated large amounts of smaller particles, ranging all the way down to dust particles. If most planetary systems go through a LHB-type event at a similar age, it is quite reasonable to assume that other stellar systems might also have similar remnant debris disks at ~600 Myr of age. However, it has been recently argued that events such that of the LHB can be triggered by sudden dynamical interactions between planets after a long quiescent period (Gomes et al. 2005). In that case, the incidence of debris disks on Hyades members is not expected to be significantly different from that of stars that are somewhat older (or younger) than them.

Here, we analyze deep MIPS 24 and 70 μm observations for a sample of 78 Hyades stars, enough to provide robust statistics on the status of debris disks at 625 Myr of age. In § 2 we describe the sample of Hyades stars, our observations, and the data reduction procedures. In § 3 we establish our data identification criteria and present our detection statistics. In § 4 we compare our detection statistics to recent Spitzer results, use our sensitivity limits and debris disk models to constrain the maximum mass of dust that could remain undetected around our targets, and discuss the implications of our results for debris disk evolution models and the LHB in the solar system.

2. OBSERVATIONS

2.1. Spitzer Sample and Observations

The majority of the 78 targets discussed in this paper were observed at 3.6, 4.5, 5.8, and 8.0 μm with the Infrared Array Camera (IRAC) and at 24, 70, and 160 μm with MIPS as part of our General Observer (GO) program 3371. This program contains 45 FGK-type Hyades members from the high-precision radial velocity (RV) survey discussed by Cochran et al. (2002) and Paulson et al. (2004). We have also included MIPS 24 and 70 μm observations of Hyades members from the Formation and Evolution of Planetary Systems Spitzer Legacy Project (program ID 148; 21 FGK-type stars) and two Guaranteed Time Observation (GTO) programs (program ID 40, 11 A-type stars; and program ID 71, 1 K0 star). Even though the MIPS photometry for some of the targets has already been discussed in the context of their respective programs (Su et al. 2006; Meyer et al. 2006), we have retrieved the MIPS data from the Spitzer archive and processed them ourselves for consistency. The Astronomical Observation Request (AOR) keys, program IDs, spectral types from the literature, and near-IR photometry (from 2MASS) for our entire sample of Hyades stars are listed in Table 1.

Given the extreme near-IR brightness of the sample, the IRAC observations of our GO program were acquired in the subarray mode (e.g., 64 frames of 0.02 s). The IRAC data were requested to try to better constrain the stellar photospheres of our targets; however, they did not fulfill their intended purpose and were not utilized in our study (see § 3.1). All the MIPS observations discussed in this paper were obtained using the MIPS pointed imaging mode. At 24 μm, one or two cycles of 3 s frames were enough to detect the stellar photospheres of the entire sample with high signal-to-noise ratio (S/N > 40). At 70 μm, the observations were designed for the 1 σ detector sensitivities to match the predicted stellar photospheres of the targets. Thus, in the absence of background noise, an IR excess 4 times larger than the photospheric flux would be detected at a 5 σ level. However, at the distance of the Hyades, the 70 μm photospheric emission of most FGK-type stars falls below the extragalactic confusion level (see § 3.2), and the observations become background-limited beyond 24 μm for most of the sample.

2.2. Data Reduction

We processed the IRAC data (available only for GO program 3371) and MIPS 24 μm data using the mosaicking and source extraction software 2dphot, which was developed as part of the Spitzer Legacy Project “From Molecular Cores to Planet Forming Disks” (Evans et al. 2006). This program is based on the mosaicking program MOPEX (MOsaic and Source EXtractor), developed by the Spitzer Science Center (SSC), and on the source extractor program DoPHOT (Schechter et al. 1993). The IRAC and MIPS 24 μm measurements for our entire sample are listed in Tables 2 and 3, respectively.

### Table 1: Sample of Hyades Stars

| Star Name     | R.A. (J2000.0) | Decl. (J2000.0) | MIPS AOR | IRAC AOR | Program ID | Spectral Type | J (mag) | H (mag) | Ks (mag) |
|---------------|---------------|----------------|----------|----------|------------|---------------|---------|---------|---------|
| BD +17 455    | 43.81800      | 17.89170       | 10853888 | 10865152 | 3371       | G7            | 7.56    | 7.21    | 7.18    |
| BD +29 503    | 44.44890      | 29.66140       | 10841856 | 10854400 | 3371       | K0            | 7.38    | 7.00    | 6.91    |
| HD 18632      | 45.01220      | 7.74980        | 10842112 | 10854656 | 3371       | K2            | 6.32    | 5.95    | 5.84    |
| HD 20430      | 49.35990      | 7.65580        | 05403904 | 12289280 | 3371       | F8            | 6.29    | 6.05    | 5.99    |
| BD +07 499    | 50.12200      | 8.45440        | 12289280 | 12288512 | 3371       | K5            | 7.54    | 6.96    | 6.88    |
| BD +23 465    | 53.20890      | 23.69240       | 10842624 | 10856192 | 3371       | K1            | 7.37    | 7.02    | 6.91    |
| HIP 17766     | 57.04970      | 7.14620        | 10843648 | 10856192 | 3371       | K6            | 8.27    | 7.62    | 7.51    |
| BD +29 503    | 57.76320      | 29.66140       | 10841856 | 10854656 | 3371       | K0            | 7.38    | 7.00    | 6.91    |
| BD +17 455    | 58.75610      | 8.45440        | 12289280 | 12288512 | 3371       | K1            | 7.37    | 7.02    | 6.91    |
| BD +29 503    | 58.77730      | 16.99840       | 10844160 | 10856960 | 3371       | K2            | 7.41    | 7.04    | 6.91    |

Notes.—Units of right ascension and declination are degrees. Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
TABLE 2
IRAC Photometry

| Star Name     | R.A. (J2000.0) | Decl. (J2000.0) | 3.6 μm Flux (mJy) | 4.5 μm Flux (mJy) | 5.8 μm Flux (mJy) | 8.0 μm Flux (mJy) |
|---------------|---------------|---------------|-------------------|-------------------|-------------------|-------------------|
| BD +17 455    | 43.81795      | 17.89166      | 384               | 251               | 149               | 65                |
| BD +29 503    | 44.44457      | 29.66151      | 482               | 286               | 166               | 98                |
| HD 18632      | 45.01211      | 7.74987       | 1390              | 800               | 498               | 300               |
| BD +07 499    | 50.12181      | 8.45457       | 462               | 279               | 170               | 99                |
| BD +23 465    | 53.20876      | 23.69213      | 500               | 278               | 157               | 91                |
| HIP 17766     | 57.04950      | 7.14626       | 302               | 156               | 117               | 59                |
| HD 286363     | 58.77703      | 16.99855      | 454               | 297               | 163               | 93                |
| BD +19 650    | 60.91259      | 19.45522      | 233               | 135               | 92                | 50                |
| HIP 19082     | 61.35694      | 19.44221      | 160               | 82                | 64                | 33                |

Notes.—A 5% error should be adopted for all IRAC fluxes. As discussed in § 3.1, even though the formal errors in our IRAC measurements are typically <1%, there is a random error floor to the best uncertainty possible with our IRAC observing techniques and data reduction process of ~5%. Units of right ascension and declination are degrees. Table 2 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

For the 70 and 160 μm data, we used MOPEX to create mosaicked images. We started from SSC pipeline version S14.4 of the median-filtered BCDs (basic calibrated data), which are optimized for point-source photometry. For each source, we created two versions of the 70 μm mosaic, one resampled to 8" pixels (close to the original size of the pixels in the detector) and the other resampled to 4" pixels. We used the former to obtain the aperture photometry and the latter to visually inspect the images for background contamination (see § 3.2). The 160 μm data were resampled to mosaics with 16" pixels.

For the 70 μm data, we used an aperture of 16" in radius and a sky annulus with an inner and outer radius of 48" and 80", respectively. From high-S/N 70 μm point-source observations we derived a multiplicative aperture correction (AC) of 1.8. This AC is in good agreement with the 1.74 value suggested by the SSC for observations with the same aperture size and similar sky annulus. Thus, we calculated the observed flux, F70, as F70 = FA70AC, where FA70 is the flux within the aperture. We estimated the 1 σ photometric uncertainty as σ = AC(rmsky)1/2, where rmsky is the flux rms of the pixels in the sky annulus and n is the number of pixels in our aperture. The 70 μm measurements for our entire sample are listed in Table 3. For the 160 μm data, we used an aperture with a radius of 32" and a sky annulus with an inner and outer radius of 48" and 80", respectively. The fluxes and uncertainty were calculated in the same way as for the 70 μm data, but adopting an AC of 2.0, appropriate for the size of the aperture and sky annulus used. The 160 μm measurements for the entire sample of FGK-type stars from program ID 3371 are also listed in Table 3 (the 160 μm data are not available for the Hyades stars from the other programs).

3. RESULTS

3.1. MIPS 24 μm Results

At 24 μm, all of our targets are detected with very high S/Ns (S/N ~ 50–300). In order to establish whether our targets show IR excess at a given wavelength, we first need to estimate the expected photospheric fluxes at that wavelength. We do so by normalizing NextGen models (Hauschildt et al. 1999) corresponding to published spectral types of our Hyades stars to the near-IR data from 2MASS listed in Table 1. We decided not to include the IRAC data in the normalization of the stellar photospheres for two reasons. First, the IRAC data are only available for the stars from program 3371, and second, we found that including IRAC fluxes does not provide a better photospheric constraint than using the 2MASS data alone. This is probably because, even for bright

TABLE 3
MIPS Photometry and Photospheric Predictions

| Star Name     | F24 (mJy) | σ24 (mJy) | P24 (mJy) | F70 (mJy) | σ70 (mJy) | P70 (mJy) | F160 (mJy) | σ160 (mJy) | P160 (mJy) |
|---------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| BD +17 455    | 9.72      | 0.095     | 10.4      | −0.97     | 3.00      | 1.22      | 21.1      | 12.50     | 0.23      |
| BD +29 503    | 12.2      | 0.093     | 14.0      | −5.07     | 2.82      | 1.64      | 7.8       | 30.60     | 0.31      |
| HD 18632      | 33.8      | 0.171     | 33.1      | 5.96      | 4.31      | 3.90      | 82.9      | 22.50     | 0.74      |
| HD 20430      | 28.1      | 0.097     | 29.3      | 11.10     | 4.58      | 3.45      | ...       | ...       | ...       |
| BD +07 499    | 13.3      | 0.096     | 13.8      | 0.81      | 2.98      | 1.62      | −39.3     | 33.00     | 0.31      |
| BD +23 465    | 12.4      | 0.093     | 13.2      | −1.97     | 2.37      | 1.55      | −20.6     | 36.90     | 0.29      |
| HIP 17766     | 7.89      | 0.080     | 7.31      | −8.01     | 2.55      | 0.85      | −11.0     | 12.60     | 0.16      |
| BD +23 571    | 8.23      | 0.086     | 9.15      | 3.07      | 2.55      | 1.08      | −15.7     | 17.70     | 0.20      |
| HD 286363     | 7.66      | 0.060     | 7.06      | 0.76      | 1.69      | 0.83      | −23.6     | 9.89      | 0.15      |
| HD 285252     | 12.2      | 0.092     | 12.4      | −2.04     | 3.22      | 1.46      | −53.5     | 25.60     | 0.27      |

Note.—Table 3 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
sources with formal errors <1%, there is a random error floor to the best uncertainty possible with our IRAC and MIPS 24 μm observing techniques and data reduction process of ~0.05 mag (Evans et al. 2006). The IRAC photometry for all the targets in our GO program 3371 is presented for completeness only (see Table 2). The expected 24 μm photospheric fluxes for our entire sample, obtained as described above, are listed in Table 3.

The magnitude of the smallest 24 μm excess emission that we can identify depends on both the uncertainty of our photometry and our ability to predict the photospheric flux. In Figure 1 we plot the distribution of observed 24 μm fluxes relative to predicted photospheric fluxes. After excluding a single outlier, this distribution can be characterized as a Gaussian distribution with a mean of 0.99 and a 1 σ dispersion of 0.06. The mean of the distribution is consistent with the absolute Spitzer calibration uncertainty at 24 μm. The dispersion of the distribution is identical to that found by Bryden et al. (2006) for FGK-type field stars, smaller than that obtained by Beichman et al. (2007) for FGK and M stars, and only slightly larger than the uncertainty floor of 0.05 mag expected for 24 μm photometry obtained with c2dphot (Evans et al. 2006). However, we note that our 1 σ dispersion in the distribution of measured-to-predicted flux ratios is significantly larger than the ~0.03 mag value achieved by Su et al. (2006) for A-type stars and by Trilling et al. (2008) for FGK-type stars. Based on the analysis of Figure 1, we conclude that only one of the Hyades stars in our sample shows a significant (>3 σ) 24 μm excess. This object is HD 28355, an A-type star that was already identified by Su et al. (2006) as having a debris disk. According to the values listed in Table 3, we find that the 24 μm flux of HD 28355 is 1.24 times the expected photospheric level, in good agreement with the 1.27 value found by Su et al. (2006).

3.2. MIPS 70 μm Results

By extrapolating the predicted 24 μm photospheric fluxes, listed in Table 3, we estimated the fluxes of the stellar photospheres that are expected at 70 μm. These predicted 70 μm photospheric fluxes are also listed in Table 3. Unlike at 24 μm, the expected photospheric flux at 70 μm of all our solar-type Hyades stars is at or below the noise of the observations. This noise is dominated by the sky pixel-to-pixel variations due to extragalactic source confusion and cirrus contamination. Bryden et al. (2006) present a detailed analysis of the sources of noise in deep 70 μm observations. They analyze the noise of images constructed by combining an increasing number of cycles (each cycle consisting of 10 frames of 10 s each). They show that beyond four cycles (a total exposure time of 400 s), the total noise becomes dominated by the extragalactic background noise. The low spatial resolution of Spitzer, combined with the high instrumental sensitivity of MIPS, implies a high incidence of extragalactic sources per beam. This extragalactic source confusion sets a firm limit (1 σ ~ 2 mJy) to the sensitivity that can be achieved with MIPS at 70 μm. This limit cannot be reduced with longer integration times. Any contamination from galactic cirrus decreases the sensitivity that can be achieved at any given field. Most of the 70 μm observations discussed in this paper amount to at least 500 s (and up to 1200 s in many cases) and hence can be characterized as background-limited. Since the background noise is highly non-Gaussian, a simple 3 σ threshold is inappropriate to prevent spurious detections. Thus, the first step in our analysis is to establish a different detection criterion. In Figure 2 we plot the S/N as a function of the measured 70 μm flux. We find that a similar number of negative and positive fluctuations exists at the 5 σ level; therefore, we consider objects with S/N ratios <5 to be nondetections. We find that only two objects, HD 28226 and HD 28355 (circles), clearly stand out as robust detections. The dotted lines delimit the 5 > S/N > −5 interval. For the deep 70 μm observations considered in this paper, the noise is dominated by the sky background variations. These variations are highly non-Gaussian and primarily due to extragalactic source confusion and cirrus contamination. As a result, there is a similar number of objects with S/N ~ 5 and −5, and we consider objects with S/N < 5 to be nondetections. Three objects, HD 27962, HD 29488, and HD 33524, have S/Ns just above 5. We consider these objects to be possible detections that need further consideration.

![Figure 1](image1.png)

**Fig. 1.**—Distribution of the observed 24 μm fluxes in units of the expected photospheric fluxes. A Gaussian distribution centered at 0.99 and with a 1 σ dispersion of 0.06 (dotted line) is shown for comparison. Only one object, HD 28355, shows a significant (>3 σ) 24 μm excess above the predicted stellar photosphere. HD 28355 is an A-type star whose excess was already identified by Su et al. (2006).

![Figure 2](image2.png)

**Fig. 2.**—S/N vs. measured 70 μm flux for our sample of Hyades stars. Two objects, HD 28226 and HD 28355 (circles), clearly stand out as robust detections. The dotted lines delimit the 5 > S/N > −5 interval. For the deep 70 μm observations considered in this paper, the noise is dominated by the sky background variations. These variations are highly non-Gaussian and primarily due to extragalactic source confusion and cirrus contamination. As a result, there is a similar number of objects with S/N ~ 5 and −5, and we consider objects with S/N < 5 to be nondetections. Three objects, HD 27962, HD 29488, and HD 33524, have S/Ns just above 5. We consider these objects to be possible detections that need further consideration.
centered on the targets. HD 28266 and HD 28355 are both A-type stars, which have already been identified by Su et al. (2006) as having a debris disk. As mentioned in § 3.1, HD 28355 also shows significant 24 m excess.

Three objects, HD 27962, HD 29488, and HD 33524, have S/Ns just above 5. We consider these objects to be possible detections that need further consideration. We inspect their high-resolution (4" pixel) mosaics (Figs. 4 and 5) to establish the spatial distribution of the 70 m emission. In the three cases we find that even though there seems to be a source near the aperture, there is a significant offset (~10'~15') between the center of the 70 m emission and the location of the Hyades target. Therefore, we conclude that the 70 m emission within these apertures is likely to be due to background contamination.

We note that one of these objects, HD 33524, has been identified by Su et al. (2006) as having a weak 70 m excess. For this object, they report a 70 m flux of 21.46 ± 2.17 mJy as opposed to our 18.5 ± 3.25 mJy (i.e., the fluxes agree very well within the uncertainties). A similar situation occurs for HD 28527. Su et al. (2006) report a 70 m flux of 37.36 ± 5.94 mJy, which also is in relative agreement with our 25.1 ± 5.08 measurement (within ~2 σ). However, since the 70 m emission does not seem to be centered at the target (Fig. 5), we do not consider this detection to be real either. An independent reanalysis and inspection of the 70 m data of HD 33254 and HD 28527 confirms that the 70 m fluxes within the apertures are not likely to be associated with the Hyades stars (K. Y. L. Su 2008, private communication). Our conservative detection criterion is also supported by the presence of negative background fluctuations at the 5~7 σ level at the location of some of the targets, such as HD 28430, shown in Figure 6.

We conclude that none of the 67 FGK-type Hyades stars in our sample are detected at 70 m, while 2 of the 11 A-type stars are. The measured 70 m fluxes for these two objects, HD 28266 and HD 28355, are 13.9 and 11.5 times the values predicted for their respective photospheres (see Table 3). We attribute these excesses, as Su et al. (2006) did, to the presence of debris disks around both of these sources.

### 3.3. MIPS 160 m Results

At 160 m, the expected photospheric levels are significantly below the noise of the observations (which are only available for the 45 FGK-type stars from program ID 3371). In order to establish the detection of any of our targets, we follow the same approach as for the 70 m data. In Figure 7 we plot the S/N as a function of the measured 160 m flux. As for the 70 m observations, we
find that a similar number of negative and positive fluctuations exist at the 5 \( \sigma \) level; therefore, we consider all the 160 \( \mu m \) measurements to be nondetections.

### 4. DISCUSSION

#### 4.1. Comparison to Recent Spitzer Results

Recent Spitzer surveys have provided robust statistics on the debris disk frequencies around nearby stars against which our results can be compared. In order to make more meaningful comparisons, we divide the sample into FGK-type stars (67 objects) and A-type stars (11 objects). There are two motivations for doing so. First, most of the previous studies are restricted to one or the other of these groups. Second, given the strong luminosity dependence on spectral type, the 70 \( \mu m \) observations are sensitive to much smaller 70 \( \mu m \) excesses (in units of photospheric fluxes) and \( L_{\text{dust}}/L_* \) values for A-type stars than for FGK-type stars.

##### 4.1.1. FGK-Type versus A-Type Stars

To estimate the sensitivity difference between the 70 \( \mu m \) observations of A-type stars and FGK-type stars, we calculate the ratio of 5 times the flux uncertainties to the estimated photospheric values (from Table 3). A cumulative histogram of this ratio is shown in Figure 8 for FGK and A-type stars. For A-type stars, the 70 \( \mu m \) observations can detect fluxes that are \( \sim 1-2 \) times those of the expected photospheres. However, for most of the FGK-type stars, the 70 \( \mu m \) observations are only sensitive enough to detect fluxes that are \( \sim 15 \) times the expected photospheric values. As discussed in § 3.2, this sensitivity limitation is mostly due to the fact that the stellar photospheres of solar-type stars, at the distance of the Hyades, fall below the 70 \( \mu m \) extragalactic confusion limit for MIPS (1 \( \sigma \sim 2 \) mJy; Bryden et al. 2006).

The difference in 70 \( \mu m \) sensitivity is even larger when it is calculated in terms of minimum detectable disk luminosity, \( L_{\text{dust}}/L_* \). Following Bryden et al. (2006), we calculate minimum disk luminosity as a function of 70 \( \mu m \) excess flux by setting the emission peak at 70 \( \mu m \) \( (T_{\text{dust}} = 52.5 \) K), according to

\[
\frac{L_{\text{dust}}}{L_*} \text{(minimum)} = 10^{-5} \left( \frac{5600 \text{ K}}{T_*} \right)^3 \frac{F_{\text{dust,70}}}{F_{\nu,70}},
\]

where \( F_{\text{dust,70}} \) is the flux of the dust and \( F_{\nu,70} \) is the flux of the stars, both at 70 \( \mu m \). By setting \( F_{\text{dust,70}} = 5\sigma_{70} - F_{\nu,70} \), we calculate the minimum \( L_{\text{dust}}/L_* \) values that are detectable for A-type and FGK-type stars. The results are shown in Figure 9, which
Fig. 5.—The 70 µm inverted gray-scale mosaics of HD 28527 (top) and HD 33254 (bottom) resampled to 4" pixels in order to gain spatial resolution. North is up and east is to the left in both images. Both objects are A-type stars identified by Su et al. (2006) as having small 70 µm excess ($F_{70}/L_{\gamma} \sim 2.7–2.9$). However, since we detect these objects at a marginal level (S/N = 4.9 and 5.6, respectively) and the emissions are not centered at the locations of the objects (circles), we do not consider the detections to be real. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 6.—The 70 µm inverted gray-scale mosaic of HD 28430 resampled to 4" pixels. North is up and east is to the left. Within the aperture centered at the target (circles), there is a flux deficit that is significant at the 6.9 $\sigma$ level. The existence of this kind of minimum strongly suggests that “detections” at the 5–7 $\sigma$ level should be interpreted with caution. [See the electronic edition of the Journal for a color version of this figure.]
demonstrates that the 70 μm observations of A-type stars are sensitive enough to detect disks with $L_{\text{dust}}/L_\star$ values in the $10^{-6}$ to $10^{-5}$ range. However, for most of the FGK-type stars, the 70 μm observations are only sensitive enough to detect disks with $L_{\text{dust}}/L_\star \geq (1-2) \times 10^{-6}$. We also use equation (1) to estimate $L_{\text{dust}}/L_\star$ values of $3.4 \times 10^{-5}$ and $4.7 \times 10^{-5}$ for the debris disks around HD 28226 and HD 28355, respectively. Since there are only two FGK-type objects for which the 70 μm observations are sensitive enough to detect disks fainter than $L_{\text{dust}}/L_\star \sim 4.0 \times 10^{-5}$, we conclude that the difference in the detection rate of debris disks around A-type stars and FGK-type stars is the result of a sensitivity bias rather than a real effect.

### 4.1.2. Comparison to FGK-Type Field Stars

Bryden et al. (2006) present 24 and 70 μm observations for 69 FGK-type nearby (distance $\sim 10–30$ pc) field stars with a median age of $\sim 4$ Gyr. They find 24 μm excess around only one of their targets. This is consistent with the 24 μm excess rate of 0% we find for our 67 FGK-type stars. At 70 μm, they identify seven debris disks. This excess rate ($\sim 10\%$), if taken at face value, seems inconsistent with our results. However, given the smaller distances to the stars involved, their survey is more sensitive than ours to faint disks. Since the stellar photospheres of their targets are above the 70 μm confusion limit of MIPS, they are able to detect the stellar photospheres of most of them and identify very faint disks ($L_{\text{dust}}/L_\star \geq 10^{-5}$). They also find that the disk frequency increases from 2% ± 2% for disks with $L_{\text{dust}}/L_\star \geq 10^{-4}$ to 12% ± 5% for disks with $L_{\text{dust}}/L_\star \geq 10^{-5}$. Recent results by Trilling et al. (2008) confirm that the frequency of debris disks with $L_{\text{dust}}/L_\star \geq 10^{-4}$ around solar-type stars is $\sim 2\%$.

Figure 9 shows that there are only 22 objects for which our 70 μm observations are sensitive enough to detect a debris disk with $L_{\text{dust}}/L_\star \geq 10^{-4}$. We use binomial statistics to show that if the incidence of disks brighter than $L_{\text{dust}}/L_\star = 10^{-4}$ is in fact 2%, as found by Bryden et al. (2006) and Trilling et al. (2008), there is a 26% probability that our survey will find zero disks. Also, given the cumulative distribution of sensitivities shown in Figure 9, we use binomial statistics to calculate the minimum disk frequencies, as a function of $L_{\text{dust}}/L_\star$, that will be excluded.
at the 1 and 2 σ level (i.e., the disk frequencies that will give our survey a 32% and 5% chance of resulting in zero detections). These disk frequencies are tabulated in Table 4.

Based on the statistics for disks with $L_{\text{disk}}/L_*$ $\geq 10^{-4}$, Table 4 suggests that a debris disk fraction in the Hyades ~2.5 and ~6 times larger than in the field can be excluded at the 1 and 2 σ level, respectively. Thus, we conclude that the debris disk fraction of the FGK-type Hyades stars (age ~625 Myr) is consistent with that in the field (age ~4 Gyr), but that ~6 times higher values cannot be excluded from the currently available data.

4.2. Comparison to Debris Disk Models

In this section we use the debris disk model developed by Augereau et al. (1999) to constrain the location and mass of the circumstellar material around HD 28266 and HD 28355, the two A-type stars identified in § 3.2 as having real 70 μm excesses. We also use this model to estimate the maximum encompassed mass of dust as a function of distance from the stars that could remain undetected around the A-type and FGK-type stars in our sample that do not show significant IR excesses.

4.2.1. The Debris Disks around HD 28266 and HD 28355

We limit the exploration of the parameter space to the disk parameters that most affect the global shape of a spectral energy distribution (SED), namely, the minimum grain size $a_{\text{min}}$, the peak surface density position $r_0$, and the total dust mass $M_{\text{dust}}$ (or, equivalently, the surface density at $r_0$). We adopt a differential grain size distribution proportional to $r^{-3.5}$ between $a_{\text{min}}$ and $a_{\text{max}}$, with $a_{\text{max}} = 1300$ μm, a value large enough to not affect the SED fitting in the wavelength range we consider. Following Augereau et al. (1999), the disk surface density $\Sigma(r)$ is parameterized by a two power-law radial profile, $\Sigma(r) = \Sigma(r_0)\sqrt{2(x^{2-2}\alpha + x^{2+2}\alpha)e^{-1/2}}$, where $x = r/r_0$, $\alpha_{\text{in}} = 10$, and $\alpha_{\text{out}} = -3$, to simulate a disk peaked around $r_0$ with a sharp inner edge and a density profile decreasing smoothly with the distance from the star beyond $r_0$. The optical properties of the grains were calculated for astronomical silicates (optical constants from Weingartner & Draine 2001) and with the Mie theory valid for hard spheres. The grain temperatures were obtained by assuming the dust particles are in thermal equilibrium with the central star. NextGen model atmosphere spectra (Hauschildt et al. 1999) scaled to the observed K-band magnitudes were used to model the stellar photospheres.

For each of the stars with 70 μm excess, HD 28266 and HD 28355, we calculated 15,000 SEDs (0.3 μm $\leq \lambda \leq 950$ μm) for 75 logarithmically spaced values of $a_{\text{min}}$ between 0.05 and 100 μm and for 200 values of $r_0$ logarithmically spaced between 10 and 500 AU. For each model, the dust mass was adjusted by a least-squares method assuming purely photospheric emission in the 2MASS bands and by fitting the measured MIPS 24 and 70 μm flux densities. The results are summarized in Table 5, and the SEDs are displayed in Figure 10. Results in Table 5 are listed for two different regimes of minimal grain sizes, namely, $a_{\text{min}} > 10$ and <0.5 μm, in order to illustrate the strong dependence of $r_0$ and $M_{\text{dust}}$ on the assumed grain size distribution.

Even though neither the position of the peak surface density $r_0$ nor the minimum grain size $a_{\text{min}}$ can be uniquely determined with so few observational constraints, some models can be eliminated. In particular, given the large luminosity of A-type stars, the small or nonexistent excess at 24 μm implies that the disks of HD 28266 and HD 28355 are significantly dust-depleted within at least ~40 AU from the star. However, “inner holes” larger than 300 AU cannot be excluded if very small grains are present (i.e., $a_{\text{min}} < 0.5$ μm). Similarly, even though the best-fit disk models imply dust masses of the order of $10^{-2}$ $M_{\odot}$, disk masses $\sim 0.1 M_{\odot}$ could be accommodated for both stars.

4.2.2. Limits on Dust Masses as a Function of Radius

In § 4.1.1 we found that the 70 μm observations of the Hyades were sensitive to significantly lower fractional disk luminosities for A-type stars than for FGK-type stars. However, since the 70 μm observations probe larger radii around A-type stars than around FGK-type stars, this implies that the mass of the grains needed to produce a given fractional luminosity, as calculated in § 4.1.1, is larger around A-type stars than it is around FGK-type stars (see Gautier et al. [2007] for a discussion of the origin of the dependence of dust-mass sensitivity on stellar luminosity). Therefore, the degree to which the MIPS observations are sensitive to smaller amounts of dust around A-type stars than around FGK-type stars is not immediately obvious. In order to explore this last point, we estimate the maximum encompassed mass of dust, as a function of distance from the stars, that could remain undetected around the A-type and FGK-type stars in our sample that do not show significant IR excesses.

Following Cieza et al. (2007), we use the optically thin disk models discussed above to constrain the maximum amount of dust that could be present within 300 AU of the A-type and FGK-type stars in our sample. Using the 70 μm 5 σ upper limits (and the 160 μm limits, when available), we calculate 15,000 models analogous to those calculated for HD 28266 and HD 28355 for each of the stars in our sample. For each model, we calculate the mass encompassed within a radius $r$ as a function of this radius. With this approach, we estimate the maximum dust mass in the circumstellar regions of the Hyades stars with no detectable emission in excess of the photospheric emission. The results for A-type and FGK-type stars for two different minimal grain size regimes ($a_{\text{min}} > 10$ μm, blue region, and $a_{\text{min}} < 0.5$ μm, red region) are shown in Figure 11. This figure shows that the absence of IR excess at 24 and 70 μm constrains the total mass of dust within 10 AU of the solar-type stars to be $< 10^{-4} M_{\odot}$. This limit is an order of magnitude lower for A-type stars. The range of encompassed dust masses as a function of radius for the best-fit
disk models of HD 28355 corresponding to the case where $a_{\text{min}} > 10 \mu m$ is shown for comparison (green region). The fact that, for FGK-type stars, the green region lies below the blue region (i.e., the case corresponding to the same grain size distribution) implies that disks similar to that found around HD 28355 would not be detectable by our observations if they were also present around the FGK-type Hyades members. Given the similarities of the inferred disk properties of HD 28355 and HD 28266 (see Table 5), the same conclusion applies for HD 28266. Thus, Figure 11 strengthens our conclusion from § 4.1.1 stating that the difference in the detection rate of debris disks around A-type and FGK-type stars is due to a sensitivity bias rather than to a real difference in the incidence or properties of debris disks around stars of different spectral types.

4.3. Debris Disk Evolution and the Late Heavy Bombardment

4.3.1. Steady State versus Stochastic Evolution

Rieke et al. (2005) study a sample of 266 A-type stars with Spitzer, ISO, or IRAS 24/25 $\mu$m data. They use this very large sample to establish statistically significant trends of IR excess with age. They find that (1) at all ages the population is dominated

![Fig. 10.—Hyades A-type stars with 70 $\mu$m excess. In each panel, the darkest region corresponds to the most likely fits to the SEDs. The dashed line shows the thermal emission for the best-fit model, while the dotted line corresponds to the total disk emission (i.e., including scattered light emission).]

![Fig. 11.—Maximum encompassed dust mass as a function of the distance from the star for the FGK-type (left) and A-type (right) stars without Spitzer excesses. The red region corresponds to mass upper limits when minimum grain sizes $a_{\text{min}}$ between 0.05 and 0.5 $\mu$m are considered, while the blue region corresponds to 10 $\mu$m < $a_{\text{min}}$ < 100 $\mu$m. The solid line indicates the mass as a function of radius for the best-fit model of HD 28355, corresponding to the case where $a_{\text{min}} > 10 \mu$m (see Table 5). The green region indicates the 1 $\sigma$ limits of the best-fit model.]

by stars with little or no IR excess, (2) stars with a wide range of excesses are seen at every age, and (3) both the frequency and the magnitude of the IR excess decreases with time. In particular, they find that the upper envelope of the evolution of the excess ratio with time can be fitted by $t_0/t$, with $t_0 \sim 150$ Myr. Similar trends are seen in the 70 $\mu$m excesses of A-type stars (Su et al. 2006), with the difference that the decay time seems to be considerably larger, $t_0 \gtrsim 400$ Myr, suggesting inside-out disk clearing.

Based on these results, Rieke et al. (2005) argue that the evolution of debris disks is the convolution of a stochastic and a steady component. They suggest that, at any given age, the debris disks detected are those that have experienced large planetesimal collisions in the recent past. This stochastic evolution is on top of a steady decrease in the number of parent bodies in the belts of planetesimals, where the dust is produced, which would explain the overall decrease of IR excess with age. However, it has also been argued that a stochastic component in the evolution of a debris disk is not necessary to explain the diversity of disk properties observed at a given age. Wyatt et al. (2007b) construct a simple collisional model, where the mass of planetesimals is constant until the largest ones reach collisional equilibrium, at which point mass falls as $1/t$. They propose that the large spread in IR properties observed at any given age can be explained in terms of the initial distributions of masses and temperatures of the planetesimal belts producing the dust. They argue that their simple model can account for the 24 and 70 $\mu$m statistics presented by Rieke et al. (2005) and Su et al. (2006) using realistic belt parameters, and thus that transient events are not required to explain the observations. Given the limited observational constraints available, the models presented by Wyatt et al. (2007b) do not rule out the possibility that stochasticity plays an important role in the evolution of most debris disks. Our results could provide additional constraints on these kinds of models because, unlike the studies by Rieke et al. (2005) and Su et al. (2006), our study provides robust statistics for the debris disks at a single, well-defined age.

### 4.3.2. Implications for the Late Heavy Bombardment in the Solar System

The 625 Myr age of the Hyades corresponds almost exactly to the era of the LHB (Tera et al. 1973; Gomes et al. 2005). Thus, if the solar-type (FGK) Hyades stars resemble the Sun at 625 Myr of age, our statistics could provide valuable clues to this important event in the history of the solar system.

The cause and duration of the LHB is still a matter of debate. Proposed causes for an intense spike in the impact rate include the formation of Uranus and Neptune (Levison et al. 2001), the presence of a fifth terrestrial planet in a low-eccentricity orbit which became dynamically unstable at an age of about 600 Myr (Chambers & Lissauer 2002), or impacts by bodies left over from planetary accretion (Morbidelli et al. 2001). More recently, Gomes et al. (2005) proposed that the LHB was triggered by the sudden migration of the giant planets that occurred after a long quiescent period of time. In their model, soon after the dissipation of the solar nebula, the orbits of Jupiter and Saturn started to slowly diverge due to interaction with the massive disk of planetesimals that was still present. They argued that $\sim 700$ Myr later, when Jupiter and Saturn crossed their $1:2$ mean motion resonance, their orbits became eccentric and temporally destabilized those of Uranus and Neptune. The reconfiguration of the orbits of the giant planets resulted in the perturbation and massive delivery of planetesimals to the inner solar system, which, according to their models, lasted between 10 and 150 Myr.

The observational signatures of a LHB-type event as seen from a distance of 46 pc are not known, but it has been suggested that they could be those of a family of rare solar-type stars characterized by the presence of a bright "hot disk" around an object hundreds of millions of years old. These objects present excess IR emission originating in the terrestrial planet regions with $F_{\text{IR}}/F_* > 10^{-4}$, a level that is $>1000$ times larger than steady state evolution models can explain (Wyatt et al. 2007a). There are currently only five known objects that fall into this category of "hot transient disks": BD +20 307 (age $\sim 300$ Myr; Song et al. 2005), HD 72905 (age $\sim 400$ Myr; Beichman et al. 2006), $\eta$ Corvi (age $\sim 1$ Gyr; Wyatt et al. 2005), HD 69830 (age $\sim 2$ Gyr; Beichman et al. 2005), and $\tau$ Ceti (age $\sim 10$ Gyr; Di Folco et al. 2007), which represent $\sim 2\%$ of all the solar-type stars surveyed. If this group of objects corresponds to those that are currently experiencing events similar to the LHB, and the Hyades stars resemble the Sun at 625 Myr of age, then the fact that none of the 67 solar-type stars in our Hyades sample has a hot transient disk implies one of two possibilities: (1) the likelihood of an event similar to the LHB is not significantly higher at $\sim 625$ Myr than it is at any other age, or (2) events like the LHB are very short spikes with a duration much closer to the lower limit of 10 Myr suggested by Gomes et al. (2005) than to their 150 Myr upper limit. If the likelihood of a LHB-type event is approximately constant with time, then a $2\%$ incidence in the solar neighborhood (median age $\sim 4000$ Myr) would imply a total duration of $\sim 80$ Myr. However, if such an event is more likely to occur around an age of $\sim 625$ Myr, then our nondetections would only be consistent with a much shorter duration. Thus, the implication of our results on the LHB could depend on the age distribution of these hot transient disks, which still remains largely unconstrained, since only five such examples are currently known. Fortunately, as more Spitzer observations are reported, this distribution will become better constrained.

Understanding the debris disk phenomenon has been a high priority of Spitzer's mission. As a result, the number of debris disk studies has increased dramatically over the last few years. Each of these studies is providing new clues and constraints from which will eventually emerge a much clearer picture of the evolution of debris disks and its connection to the history of the solar system.
REFERENCES

Augereau, J. C., Lagrange, A. M., Mouillet, D., Papaloizou, J. C. B., & Grorod, P. A. 1999, A&A, 348, 557
Aumann, H. H., et al. 1984, ApJ, 278, L23
Beichman, C. A., Fridlund, M., Traub, W. A., Stapelfeldt, K. R., Quirrenbach, A., & Seager, S. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 915
Beichman, C. A., et al. 2005, ApJ, 622, 1160
———. 2006, ApJ, 652, 1674
Bryden, G., et al. 2006, ApJ, 636, 1098
Chambers, J. E., & Lissauer, J. J. 2002, 33rd Annual Lunar and Planetary Science Conference, Abstr. 1093
Cieza, L., et al. 2007, ApJ, 667, 308
Cochran, W. D., Hatzes, A. P., & Paulson, D. B. 2002, AJ, 124, 565
Cohen, B. A. 2002, 33rd Annual Lunar and Planetary Science Conference, Abstr. 1984
Di Folco, E., et al. 2007, A&A, 475, 243
Evans, N. J., et al. 2006, Final Delivery of Data from the c2d Legacy Project: IRAC and MIPS (Pasadena: SSC), http://ssc.spitzer.caltech.edu/legacy
Gautier, T. N., III, et al. 2007, ApJ, 667, 527
Gomes, R., Levison, H. F., Tsiganis, K., & Morbidelli, A. 2005, Nature, 435, 466
Habing, H. J., et al. 2001, A&A, 365, 545
Hauschildt, P. H., Allard, F., & Baron, E. 1999, ApJ, 512, 377
Levison, H. F., Dones, L., Chapman, C. R., Stern, S. A., Duncan, M. J., & Zahnle, K. 2001, Icarus, 151, 286
Meyer, M. R., et al. 2006, PASP, 118, 1690
Morbidelli, A., Petit, J.-M., Gladman, B., & Chambers, J. 2001, Meteoritics Planet. Sci., 36, 371
Neukum, G., & Ivanov, B. A. 1994, in Hazards Due to Comets and Asteroids, ed. T. Gehrels, M. S. Matthew, & A. Schumann (Tucson: Univ. Arizona Press), 359
Paulson, D. B., Cochran, W. D., & Hatzes, A. P. 2004, AJ, 127, 3579
Paulson, D. B., Sneden, C., & Cochran, W. D. 2003, AJ, 125, 3185
Rieke, G., et al. 2005, ApJ, 620, 1010
Ryder, G. 1990, EOS Trans., 71, 313
Schechter, P. L., Mateo, M., & Saha, A. 1993, PASP, 105, 1342
Song, I., Zuckerman, B., Weinberger, A. J., & Becklin, E. E. 2005, Nature, 436, 363
Spangler, C., Sargent, A. I., Silverstone, M. D., Becklin, E. E., & Zuckerman, B. 2001, ApJ, 555, 932
Su, K. Y. L., et al. 2006, ApJ, 653, 675
Tera, F., Papanastassiou, D. A., & Wasserburg, G. J. 1973, Abstr. Lunar Planet. Sci. Conf., 4, 723
Trilling, D. E., et al. 2008, ApJ, 674, 1086
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Wetherill, G. W. 1975, 6th Lunar Sci. Conf., 2, 1539
———. 1977, 8th Lunar Sci. Conf., 1, 1
Wyatt, M. C., Greaves, J. S., Dent, W. R. F., & Coulson, I. M. 2005, ApJ, 620, 492
Wyatt, M. C., Smith, R., Greaves, J. S., Beachman, C. A., Bryden, G., & Lisse, C. M. 2007a, ApJ, 658, 569
Wyatt, M. C., Smith, R., Su, K. Y. L., Rieke, G. H., Greaves, J. S., Beachman, C. A., & Bryden, G. 2007b, ApJ, 663, 365
Yamashita, T., Handa, T., Omodaka, T., Kitamura, Y., Kawazoe, E., Hayashi, S. S., & Kaifu, N. 1993, ApJ, 402, L65