

DEBRIS DISKS AROUND SUN-LIKE STARS

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ABSTRACT

We have observed nearly 200 FGK stars at 24 and 70 μm with the *Spitzer Space Telescope*. We identify excess infrared emission, including a number of cases where the observed flux is more than 10 times brighter than the predicted photospheric flux, and interpret these signatures as evidence of debris disks in those systems. We combine this sample of FGK stars with similar published results to produce a sample of more than 350 main sequence AFGKM stars. The incidence of debris disks is $4.2^{+2.0}_{-1.1}\%$ at 24 μm for a sample of 213 Sun-like (FG) stars and $16.4^{+2.8}_{-2.9}\%$ at 70 μm for 225 Sun-like (FG) stars. We find that the excess rates for A, F, G, and K stars are statistically indistinguishable, but with a suggestion of decreasing excess rate toward the later spectral types; this may be an age effect. The lack of strong trend among FGK stars of comparable ages is surprising, given the factor of 50 change in stellar luminosity across this spectral range. We also find that the incidence of debris disks declines very slowly beyond ages of 1 billion years.

Subject headings: circumstellar matter — infrared: stars — planetary systems: formation

Online material: color figures

1. INTRODUCTION

Planetary system formation must be studied through various indirect means due to the relative faintness of distant planets and the long timescales over which planetary system evolution takes place. One powerful technique has advanced substantially in the era of the *Spitzer Space Telescope*: investigations of dusty debris disks around mature, main sequence stars. Debris disks arise from populations of planetesimals that remain from the era of planet formation; the analogs in our solar system are the asteroid belt and the Kuiper Belt. Any system that possesses a debris disk necessarily has progressed toward forming a planetary system to some degree.

The many small bodies that inhabit a debris disk can, on occasion, collide, producing a shower of fragments that grind each other down to dust particles. These dust grains can be heated by the central star to temperatures ~ 100 K, where they can be detected at wavelengths of 10–100 μm . Data from the *Infrared Astronomical Satellite (IRAS)* and *Infrared Space Observatory (ISO)* were used to identify and characterize debris disks (e.g., Aumann et al. 1984; Decin et al. 2000; Spangler et al. 2001; Habing et al. 2001; Decin et al. 2003; Rhee et al. 2007). The Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004) offers substantially improved sensitivities at 24 and 70 μm and therefore can be used to advance the study of debris disks and measure the fraction of stars that possess colliding swarms of remnant planetesimals.

A number of these surveys have been carried out using MIPS. Rieke et al. (2005) and Su et al. (2006) observed hundreds of A stars and found that the number of A stars showing thermal infrared excess suggestive of collisionally produced dust decreases as a function of stellar age, from 50% or more at ages just past the gas dissipation age of 10 Myr to 30% at 500 Myr. The excess

rates are lower for older and lower mass stars. Bryden et al. (2006) found that the excess rate is around 15% for stars of mass and age similar to our Sun (for a sample of 69 stars). Gautier et al. (2007) did not detect any 24 or 70 μm excesses suggestive of debris disks in a sample of 60 field (old) M stars (with only 13 strongly detected at 70 μm). Finally, multiplicity appears to play a significant role in modulating debris disks, as Trilling et al. (2007) found that the debris disk rate for A and F binaries was higher than that for single stars of similar spectral types.

We present here a survey for excesses around almost 200 F, G, and K stars, with ages and masses similar to that of our Sun. (Some of these data were published in Bryden et al. [2006].) We characterize the excesses that we find and present a few systems of particular interest. We create a larger sample of FGK stars by adding 75 stars from a similar survey, and derive excess rates as a function of spectral type and as a function of age. Finally, we discuss the implications of our results for planetary system formation.

2. SAMPLE SELECTION

The data presented here originate in two separate observing programs. The majority are from a survey targeting nearby late F, G, and early K “solar type” stars (*Spitzer* GTO program 41). Results for 69 stars from this program were published in Bryden et al. (2006, hereafter B06), and the present paper completes the analysis of data from that program. For completeness, all targets that appeared in B06 are also included in this paper. The remainder of the data belong to a survey for debris disks among F stars (*Spitzer* GTO program 30211). Stars in this spectral type range were omitted from previous *Spitzer* disk surveys, and have particular relevance in determining the nature of the transition from the high A star debris disk incidence to the more modest incidence for Sun-like stars. Furthermore, these 49 F stars will serve as a useful control sample to the Trilling et al. (2007) result that binary A and F stars have a relatively high excess rate. We combine the data from these two samples here to give continuous coverage, a large sample of stars, and overall view of debris disks for F0–K5 stars. We refer to the combined sample of 193 stars (PID 41 plus PID 30211) as our FGK sample. Relevant information for the combined target list is given in Table 1. Figures 1–4 show

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TABLE 1
TARGET INFORMATION

Name (HD)	Spectral Type	V (mag)	d (pc)	Age (Gyr)	[M/H]	Reference
63.....	F5	7.15	50.48	2.9	-0.08	M
142 ^a	G11 V	5.70	25.64	2.88	0.04	Ca
166.....	K0 V	6.13	13.70	5.01	-0.30	Ca
693.....	F5 V	4.89	18.89	5.16	-0.34	Ca
1237 ^a	G6 V	6.7	17.62	2.75	0.10	Ca
1539.....	F5	7.03	46.32	2.9	0.03	M
1581.....	F9 V	4.20	8.59	3.02	-0.10	Ca
3126.....	F2	6.92	41.51	3.5	-0.22	M
3296.....	F5	6.61	47.19	2.5	0.01	M
3302.....	F6 V	5.52	36.22	7.76	-0.02	M
3651 ^a	K0 V	5.80	11.11	5.89	0.26	Hy
3795.....	G3 V	6.14	28.56	7.24	-0.73	Ca
3823.....	G1 V	5.88	25.47	5.50	-0.35	Ca
3861.....	F5	6.53	33.34	3.4	0.03	M
4307.....	G2 V	6.15	31.86	7.76	-0.36	Ca
4628.....	K2 V	5.75	7.46	8.13	-0.29	Ca
7570.....	F8 V	4.96	15.05	4.33	0.08	Ca
8070.....	F2	6.66	48.69	2.5	-0.20	M
8574 ^a	F8	7.8	44.15	7.24	-0.23	M
9826 ^a	F8 V	4.09	13.47	6.31	-0.03	Ca
10476.....	K1 V	5.20	7.47	4.57	-0.20	Ca
10647 ^a	F9 V	5.52	17.35	6.3	-0.11	M
10697 ^a	G5 IV	6.29	32.56	7.41	0.10	Ca
10800.....	G2 V	5.89	27.13	7.37	0.03	M
13445 ^a	K1 V	6.17	10.95	5.56	-0.21	Ca
13555.....	F5 V	5.24	30.13	2.74	-0.18	Ca
14412.....	G5 V	6.34	12.42	3.31	-0.53	Ca
14802.....	G2 V	5.19	21.93	6.76	0.00	Ca
15335.....	G0 V	5.91	30.79	7.76	-0.22	Ca
15798.....	F5 V	4.75	25.82	3.16	-0.30	Ca
16160.....	K3 V	5.82	7.21	5.4 ^b	-0.04	Hy
17051 ^a	G0 V	5.40	17.24	2.43	-0.04	Ca
17925.....	K1 V	6.00	10.38	0.19	-0.15	Ca
19373.....	G0 V	4.05	10.53	5.89	0.03	Ca
19994 ^a	F8 V	5.06	22.38	3.55	0.09	Ca
20367 ^a	G0	6.41	27.13	...	-0.01	M
20630.....	G5 Ve	4.83	9.16	0.29	-0.01	Ca
20766.....	G2 V	5.54	12.12	5.20	-0.20	Ca
20807.....	G1 V	5.24	12.08	7.88	-0.20	Ca
22484.....	F8 V	4.28	16.84	8.32	0.00	Ca
23079 ^a	G0 V	7.1	34.6	7.89	-0.12	M
23596 ^a	F8	7.24	51.98	...	0.04	M
26923.....	G0 IV	6.33	21.19	...	0.17	Ca
27442.....	K2 Iva	4.44	18.23	6.6	0.22	Ca
28185 ^a	G5	7.81	39.56	3.45	0.25	So
30495.....	G1 V	5.50	13.32	1.32	0.10	Ca
30652.....	F6 V	3.19	8.03	1.55	0.01	M
33262.....	F7 V	4.72	11.65	3.52	-0.23	Ca
33564 ^a	F6 V	5.10	20.98	3.48	-0.11	M
33636 ^a	G0	7.06	28.69	3.24	-0.14	M
34411.....	G1.5 IV-V	4.70	12.65	6.76	-0.08	Ca
34721.....	G0 V	5.96	24.93	6.17	-0.25	Ca
35296.....	F8 Ve	5.00	14.66	3.76	0.00	Ca
37394.....	K1 Ve	6.23	12.09	0.49	-0.20	Ca
39091 ^a	G1 V	5.67	18.21	5.609	0.04	M
40979 ^a	F8	6.75	148.37	...	-0.03	M
43162.....	G5 V	6.37	16.69	0.37	-0.16	Hy
43834.....	G6 V	5.09	10.15	7.61	0.00	Ca
50554 ^a	F8 V	6.86	31.03	4.68	-0.12	M
50692.....	G0 V	5.76	17.27	4.47	-0.11	M
52265 ^a	G0	6.30	28.07	6.03	0.21	Ca
52711.....	G4 V	5.93	19.09	4.77	-0.16	Ca
55575.....	G0 V	5.55	16.86	4.57	-0.28	Ca
57703.....	F2	6.78	44.09	2.3	-0.07	M

TABLE 1—Continued

Name (HD)	Spectral Type	V (mag)	d (pc)	Age (Gyr)	[M/H]	Reference
58855.....	F6 V	5.37	19.90	3.6	-0.31	Ca
60912.....	F5	6.91	46.43	2.9	-0.04	M
62613.....	G8 V	6.56	17.04	3.09	-0.20	Hy
63333.....	F5	7.11	43.07	5.5	-0.39	Ca
68456.....	F5 V	4.76	21.39	2.43	-0.36	Ca
69830 ^a	K0 V	5.95	12.58	4.68	-0.03	Ca
69897.....	F6 V	5.10	15.67	3.55	-0.26	Ca
70843.....	F5	7.04	46.53	1.6	-0.01	M
71148.....	G5 V	6.30	21.79	4.68	0.07	M
71640.....	F5	7.41	44.92	5.7	-0.09	M
72905.....	G1.5 V	5.65	13.85	0.42	-0.08	Ca
75616.....	F5	6.99	35.61	4.8	-0.17	M
75732 ^a	G8 V	5.95	12.53	6.46	0.40	Ca
76151.....	G3 V	6.00	11.29	1.84	-0.02	Ca
77967.....	F0	6.60	40.7	3.5	-0.37	M
79392.....	F2	6.760	50.53	1.8	-0.24	M
80218.....	F5	6.629	39.20	6.4	-0.28	Ca
82943 ^a	G0	6.54	27.46	4.07	0.32	Ca
83451.....	F5	7.14	48.47	3.8	-0.14	M
83525.....	F5	6.91	48.38	5.3	-0.06	M
84117.....	G0 V	4.94	14.88	4.24	-0.14	M
84737.....	G0.5 Va	5.10	18.43	11.75	0.04	Ca
86147.....	F5	6.72	45.11	2.8	0.03	M
88230.....	K2 Ve	6.61	4.69	4.68	-0.93	Ce
88984.....	F5	7.30	51.39	4.4	-0.29	M
90839.....	F8 V	4.83	12.82	3.39	-0.18	Ca
93081.....	F5	7.11	51.36	3.5	-0.23	M
94388.....	F6 V	5.24	31.34	3.16	0.07	Ca
95128 ^a	G0 V	5.10	13.91	6.03	0.01	Ca
99126.....	F5	6.96	47.37	5.7	-0.16	M
100067.....	F5	7.30	40.77	5.4	-0.34	M
101259.....	G6/8 V	6.42	64.72	10.96	-0.60	VF
101501.....	G8 Ve	5.32	9.54	1.12	0.03	Ca
102438.....	G5 V	6.48	17.77	...	-0.36	Hy
102870.....	F9 V	3.61	10.90	4.47	0.20	Ca
103773.....	F5	6.87	49.95	2.4	0.06	M
104731.....	F6 V	5.15	24.20	1.83	-0.21	Ca
104985 ^a	G9 III	5.80	102.04	...	-0.18	M
105912.....	F5	6.95	50.25	1.8	-0.04	M
109756.....	F5	6.98	46.55	3.4	-0.22	M
110897.....	G0 V	6.00	17.37	9.7	-0.59	Ca
111395.....	G7 V	6.31	17.17	1.23	0.18	Hy
111545.....	F5	6.9	48.45	1.7	-0.02	M
112164.....	G1 V	5.89	39.73	3.43	0.24	Ca
114613.....	G3 V	4.85	20.48	5.27	0.16	VF
114710.....	F9.5 V	4.26	9.15	2.29	0.06	Ca
114729 ^a	G3 V	6.69	35.00	6.76	-0.26	FV
114783 ^a	K0 V	7.57	20.43	4.37	-0.11	Hy
115383.....	G0 V	5.22	17.95	0.40	0.04	Ca
115617.....	G5 V	4.74	8.53	6.31	-0.03	Ca
117043.....	G6	6.50	21.34	...	0.22	Hy
117176 ^a	G5 V	5.00	18.11	5.37	-0.09	Ca
118972.....	K1	6.93	15.60	...	-0.03	Hy
120005.....	F5	6.50	44.92	2.9	0.05	M
120136 ^a	F7 V	4.50	13.51	1.91	0.30	Ca
120690.....	G5 V	6.45	19.92	2.24	-0.11	Ca
122862.....	G2.5 IV	6.02	28.68	6.11	-0.11	M
123691.....	F2	6.80	50.89	1.5	-0.09	M
126660.....	F7 V	4.10	14.57	2.76	-0.05	Ca
127334.....	G5 V	6.40	23.57	6.92	0.05	Ca
128311 ^a	K0	7.51	16.57	...	0.08	Hy
130460.....	F5	7.23	48.31	3.5	-0.03	M
130948.....	G2 V	5.88	17.94	0.87	0.20	Ca
133002.....	F9 V	5.64	43.33	2.459	...	...
134083.....	F5 V	4.93	19.72	1.73	0.00	Ca

TABLE 1—Continued

Name (HD)	Spectral Type	<i>V</i> (mag)	<i>d</i> (pc)	Age (Gyr)	[M/H]	Reference
134987 ^a	G5 V	6.45	25.65	7.76	0.36	Ca
136064.....	F8 V	5.10	25.31	4.64	-0.10	Ca
136118 ^a	F8	6.94	52.27	...	-0.15	M
141128.....	F5	7.01	51.02	3	-0.24	M
142373.....	F9 V	4.62	15.85	8.13	-0.40	Ca
142860.....	F6 IV	3.85	11.12	2.88	-0.13	Ca
143105.....	F5	6.76	46.08	3.3	-0.10	M
143761 ^a	G0 V	5.40	17.43	7.41	-0.26	Ca
145675 ^a	K0 V	6.67	18.15	6.92	0.50	Ca
146233.....	G1 V	5.50	15.36	4.57	0.05	Ca
149661.....	K2 V	5.76	9.78	1.17	0.00	Hy
152391.....	G8 V	6.64	16.94	0.58	-0.18	Hy
154088.....	G8 IV-V	6.59	18.08	5.89	0.30	Hy
157214.....	G2 V	5.40	13.57	6.46	-0.41	Ca
160691 ^a	G3 IV-V	5.15	15.28	6.67	0.16	Ca
166620.....	K2 V	6.37	11.10	5.01	0.07	Hy
168151.....	F5V	5.03	23.50	2.53	-0.17	Ca
168443 ^a	G5V	6.92	37.88	8.51	0.10	Go
169830 ^a	F8	5.91	36.32	7.24	0.13	Ca
171886.....	F5	7.18	49.65	3.7	-0.33	M
173667.....	F6 V	4.20	19.09	3.39	-0.01	Ca
176441.....	F5	7.08	44.72	3.7	-0.27	M
177830 ^a	K0	7.18	59.03	8.5	0.36	Go
181321.....	G5 V	6.49	20.86	0.5	...	...
181655.....	G8 V	6.31	25.23	4.57	0.02	VF
185144.....	K0 V	4.70	5.61	3.24	-0.14	Hy
186408.....	G1.5 V	5.96	21.62	10.4	0.08	Ca
186427 ^a	G3 V	6.20	21.41	7.41	0.08	Ca
188376.....	G5 V:	4.70	23.79	4.47	-0.13	Ca
189567.....	G2 V	6.07	17.71	...	-0.30	Ca
190007.....	K4 V	7.48	13.11	1.5 ^b	...	...
190248.....	G7 IV	3.56	6.11	...	0.32	Ca
191408.....	K3 V	5.31	6.05	7.88	-0.58	Ca
193664.....	G3 V	5.93	17.57	4.7	-0.18	M
196050 ^a	G3 V	7.6	46.93	...	0.23	FV
196378.....	F8 V	5.12	24.20	6.02	-0.30	Ca
196761.....	G8 V	6.37	14.65	4.27	-0.60	Hy
197692.....	F5 V	4.15	14.67	1.94	0.04	Ca
200433.....	F5	6.92	48.36	1.4	-0.09	M
202884.....	F5	7.27	42.05	5.2	-0.29	M
203608.....	F8 V	4.22	9.22	10.196	-0.64	Ca
206860.....	G0 V	6.00	18.39	5.00	-0.20	Ca
207129.....	G0 V	5.58	15.64	5.76	-0.15	Ca
209100.....	K4.5 V	4.69	3.63	1.38	0.04	Ca
210277 ^a	G0 V	6.63	21.29	6.76	0.22	Ca
210302.....	F6 V	4.92	18.74	5.37	0.06	Ca
210918.....	G5 V	6.26	22.13	3.85	-0.18	Ca
212330.....	G3 IV	5.31	20.49	7.94	0.00	Ca
212695.....	F5	6.95	51.10	2.3	-0.05	M
213240 ^a	G0 V	6.80	40.75	2.77	0.04	M
216345.....	G8III	10.21	100	...	...	...
216437 ^a	G2.5 IV	6.06	26.52	7.15	0.10	Ca
216803.....	K4 V	6.48	7.64	0.2 ^b	0.07	Sa
217014 ^a	G4 V	5.49	17.12	7.41	0.05	Ca
217813.....	G5	6.66	24.27	0.71	-0.07	M
219134.....	K3 V	5.56	6.53	...	0.20	Hy

TABLE 1—Continued

Name (HD)	Spectral Type	<i>V</i> (mag)	<i>d</i> (pc)	Age (Gyr)	[M/H]	Reference
219983.....	F2	6.67	47.71	4.7	-0.27	M
220182.....	K1	7.36	21.92	0.26	0.01	Hy
221420.....	G2 V	5.82	31.76	5.52	0.37	So
222143.....	G5	6.58	23.12	...	0.08	Hy
222368.....	F7 V	4.13	13.79	3.93	-0.18	Ca
222404 ^a	K1 IV	3.23	13.79	...	-0.05	Ca
222582 ^a	G3 V	7.70	41.95	6.63	0.02	Go
225239.....	G2 V	6.10	36.79	...	-0.50	Ca

NOTES.—Spectral types and *V* magnitudes are from B06 and from SIMBAD and Hipparcos. Ages are from B06 and from Nordstrom et al. (2004) except as indicated. To date, Barnes (2007) has derived ages for ~15% of the stars in this sample, and in general the agreement with our compiled literature values is good. When the number examined becomes a significant fraction of the total sample, we will reexamine excesses as a function of age using the new, systematic age definitions (future work). Distances are from *Hipparcos* (Perryman et al. 1997). A number of stars have no good ages, and a handful have no good metallicities. Metallicities are from the indicated references: (Ca) Cayrel de Strobel et al. (2001); (FV) Fischer & Valenti (2005); (Go) Gonzelaz et al. (2001); (Hy) Haywood (2001); (M) Marsakov & Shevelev (1995); (Sa) Santos et al. (2001); (So) Sousa et al. (2006); (VF) Valenti & Fischer (2005).

^a Star with known planet(s).

^b Age from Barnes (2007).

the distributions of targets as functions of spectral type, distance, age, and metallicity.

2.1. *F Star Sample*

Our target list was assembled in the following way. A list of main sequence F0–F5 stars was created from the *Hipparcos* database, in order of increasing distance from the Earth. All stars that were known to be members of multiple systems were removed (by vetting against the CCDM catalog). Next, systems that were obviously young (less than 1 Gyr) were removed, using the measurements of Nordstrom et al. (2004). The average age of our sample is around 3 Gyr (compare to the average age of the “solar type” FGK sample presented in § 2.2 of around 5 Gyr). We used the IPAC IBIS tool to extract the infrared background and confusion levels from the *IRAS* data for each remaining target, compared the predicted target photospheric flux to the confusion per MIPS

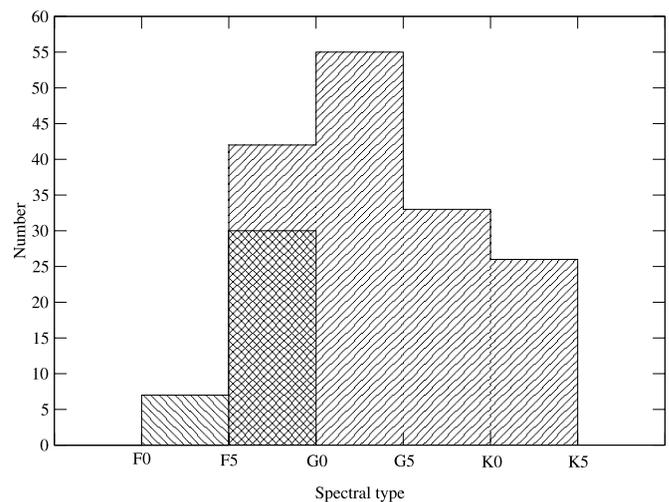


FIG. 1.—Distribution of spectral types for the 193 stars presented here. Hashes from bottom right to top left show stars from PID 30211, and hashes from bottom left to top right show stars from PID 41. Most of the targets in PID 30211 are F5 stars (difficult to see in this representation).

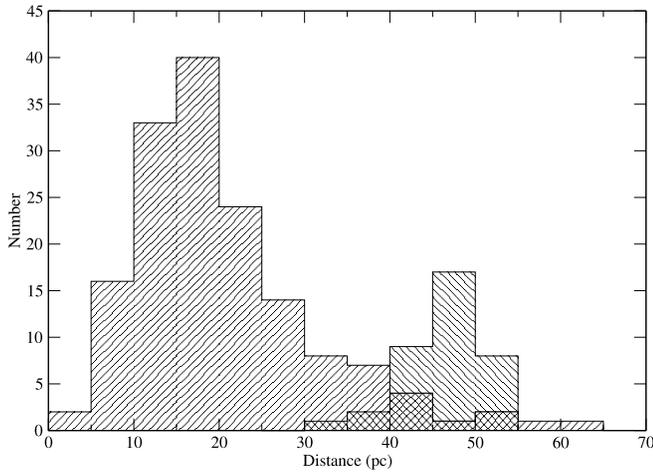


FIG. 2.—Histogram of distances for the 193 stars presented here. Three stars from PID 41 have distances off this plot: two around 100 pc, and one around 150 pc (Table 1). As in Fig. 1, hatch marks from bottom left to top right show stars from PID 41, and hatch marks from bottom right to top left show stars from PID 30211.

beam, and discarded targets with predicted $S/N < 3$. Finally, we discarded targets requiring $70 \mu\text{m}$ integration times longer than 1300 s (12 cycles of 10 s integrations); targets fainter than this rapidly become very expensive with questionable return. These selection criteria left 49 targets as our final target list. Here we present the 37 of those targets observed to date; the remaining stragglers will be published in a future paper.

2.2. “Solar Type” Sample

The “solar type” sample selection is described in detail in B06. We briefly summarize that description here. This program consists of two overlapping sets of stars: those that meet strict selection criteria for an unbiased sample, and those that are known to harbor planets. In both cases, only stars with spectral type similar to the Sun are considered. Stars with spectral type F5 to K5 and luminosity class IV or V were included, with the final list chosen by expected signal-to-noise ratio (S/N) for photospheric flux. In addition, a minimum photospheric $70 \mu\text{m}$ flux was set for each spectral type bin: 20 mJy for F5–F9 stars, 10 mJy for G0–G4, and 5 mJy for G5–K5. There is no explicit selection based on stellar age or metallicity; however, the $70 \mu\text{m}$ brightness and S/N

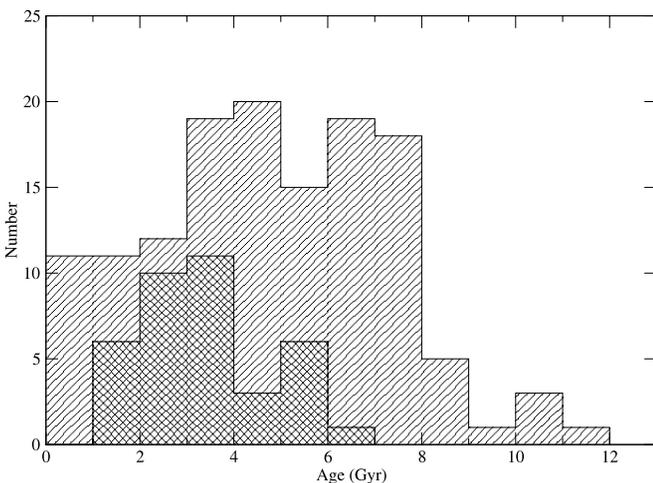


FIG. 3.—Histogram of ages for the 193 stars presented here. As in previous figures, hatch marks from bottom left to top right show stars from PID 41, and hatch marks from bottom right to top left show stars from PID 30211.

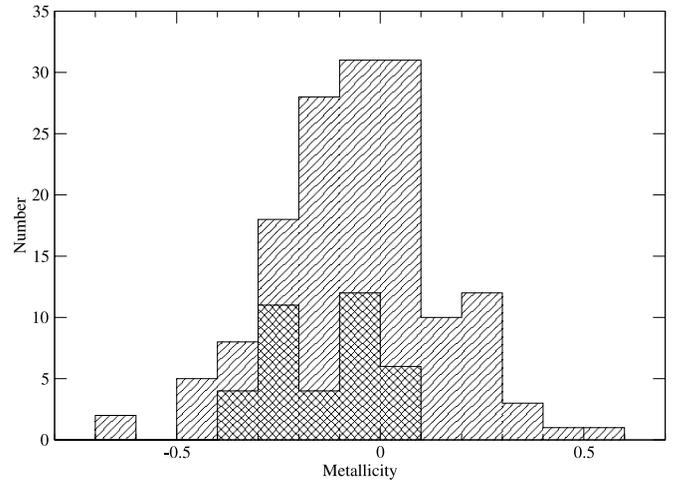


FIG. 4.—Metallicities for the 189 stars presented here with known metallicities (see Table 1). As in previous figures, hatch marks from bottom left to top right show stars from PID 41, and hatch marks from bottom right to top left show stars from PID 30211.

thresholds are relaxed in some cases to allow stars with well-determined ages into the sample. Close, resolved binary systems are excluded. The total sample presented here is 156 stars (non-planet stars and planet stars, combined). A companion paper (Bryden et al. 2007) describes the planet-bearing sample in more detail.

3. OBSERVATIONS AND DATA REDUCTION

A listing of the observations for these programs is given in Table 2. All *Spitzer* observations reported here were made between 2004 January and 2007 March. We used MIPS to observe each system at $24 \mu\text{m}$ and $70 \mu\text{m}$ (effective wavelengths 23.68 and $71.42 \mu\text{m}$, respectively). All stars were observed in MIPS Photometry small-field mode. The $24 \mu\text{m}$ observations all used 3 s DCEs (data collection events) and a single template cycle (with a few exceptions; see Table 2). The $70 \mu\text{m}$ observations typically used 10 s DCEs and 5–10 template cycles.

Overall, our data analysis is similar to that previously described in Beichman et al. (2005a, 2006b) and B06. The data reduction is based on the DAT software developed by the MIPS instrument team (Gordon et al. 2005). At $24 \mu\text{m}$, image flats are chosen as a function of scan mirror position to correct for dust spots (Engelbracht et al. 2007a). Images were mosaicked from individual frames with half-pixel subsampling. We carried out aperture photometry on reduced images as described in Beichman et al. (2005a) using an aperture of six $2.55''$ pixels, a sky annulus of 12–17 pixels, a calibration factor of $1.047 \mu\text{Jy arcsec}^{-2}/(\text{DN s}^{-1})$, and an aperture correction of 1.15. At $70 \mu\text{m}$ we used images processed beyond the standard DAT software to correct for time-dependent transients, corrections that can significantly improve the sensitivity of the measurements (Gordon et al. 2007). Because the accuracy of the $70 \mu\text{m}$ data is limited by background noise, rather than instrumental effects, a very small photometric aperture was used to maximize S/N —just 1.5 pixels in radius, requiring an aperture correction of 1.79. An annulus with an inner radius of 4 pixels and an outer radius of 8 pixels was used to measure the sky background around each target. The flux level is calibrated at $16.5 \text{ mJy arcsec}^{-2}/\text{MIPS}_{70_unit}$, with a default color correction of 1.00 (MIPS_{70_units} are based on the ratio of the measured signal to the stimulator flash signal). For both the 24 and $70 \mu\text{m}$ data, neighboring point sources were subtracted from the images before measuring the sky brightness.

TABLE 2
OBSERVING LOG

NAME (HD)	INTEGRATION TIME (s)		AOR KEY ^a	PID
	24 μ m	70 μ m		
63.....	48	355	17346304	30211
142.....	0	1090	12715008	41
142.....	48	355	4082176	41
166.....	48	440	4030720	41
693.....	48	440	4030976	41
1237.....	48	1300	4060672	41
1539.....	48	231	17343232	30211
1581.....	48	126	4031232	41
3126.....	48	231	17337600	30211
3296.....	48	132	17340672	30211
3302.....	48	440	4031488	41
3651.....	48	231	4031744	41
3795.....	48	650	4032000	41
3823.....	48	440	4032256	41
3861.....	48	107	17335552	30211
4307.....	48	650	4032512	41
4628.....	48	126	4032768	41
7570.....	48	231	4033024	41
8070.....	48	231	17341696	30211
8574.....	0	1007	4005376	41
8574.....	92	2181	8775936	41
9826.....	48	231	4033280	41
10476.....	48	126	4033536	41
10647.....	136	336	7865856	717
10697.....	48	881	4033792	41
10800.....	48	440	4034048	41
13445.....	48	126	4034304	41
13555.....	48	440	4034560	41
14412.....	48	881	4034816	41
14802.....	48	126	4035072	41
15335.....	48	650	4035328	41
15798.....	48	440	4035584	41
16160.....	48	231	4035840	41
17051.....	48	355	4036096	41
17925.....	48	126	4036352	41
19373.....	48	126	4036608	41
19994.....	48	440	4080640	41
20367.....	48	1300	12711936	41
20630.....	48	126	4036864	41
20766.....	48	231	4037120	41
20807.....	48	440	4037376	41
22484.....	48	231	4006400	41
23079.....	48	2181	4080384	41
23596.....	48	2181	12711168	41
26923.....	48	1300	4060928	41
27442.....	48	126	4081152	41
28185.....	136	2181	4005632	41
30495.....	48	231	4037632	41
30652.....	48	231	4037888	41
33262.....	48	126	4038144	41
33564.....	48	231	4038400	41
33636.....	0	1300	4059136	41
33636.....	48	2181	8777728	41
34411.....	48	126	4038656	41
34721.....	48	650	4038912	41
35296.....	48	231	4061184	41
37394.....	48	126	4039168	41
39091.....	48	355	4039424	41
40979.....	48	2181	12711680	41
43162.....	48	1007	4039680	41
43834.....	48	126	4039936	41
50554.....	0	1300	4080128	41
50554.....	48	2181	8775680	41

TABLE 2—Continued

NAME (HD)	INTEGRATION TIME (s)		AOR KEY ^a	PID
	24 μ m	70 μ m		
50692.....	48	440	4040192	41
52265.....	0	1090	12715776	41
52265.....	48	1090	4062976	41
52711.....	48	440	4040448	41
55575.....	48	355	4040704	41
57703.....	48	231	17338880	30211
58855.....	48	355	4040960	41
60912.....	48	231	17342976	30211
62613.....	48	1090	4041216	41
63333.....	48	231	17338112	30211
68456.....	48	231	4041472	41
69830.....	48	355	4041728	41
69897.....	48	231	4006144	41
70843.....	48	231	17344000	30211
71148.....	48	881	4041984	41
71640.....	48	355	17346560	30211
72905.....	48	355	4042240	41
75616.....	48	231	17336064	30211
75732.....	48	440	4042496	41
76151.....	48	545	4042752	41
77967.....	48	126	17336832	30211
79392.....	48	231	17342720	30211
80218.....	48	107	17336576	30211
82943.....	48	1636	4063232	41
83451.....	48	231	17342464	30211
83525.....	48	231	17341952	30211
84117.....	48	126	4043008	41
84737.....	48	231	4043264	41
86147.....	48	132	17340416	30211
88230.....	48	231	4043776	41
88984.....	48	355	17347840	30211
90839.....	48	231	4006656	41
93081.....	48	355	17345024	30211
94388.....	48	440	4044032	41
95128.....	48	231	4044288	41
99126.....	48	231	17341440	30211
100067.....	48	355	17337088	30211
101259.....	48	1090	4044544	41
101501.....	48	231	4044800	41
102438.....	48	1090	4045056	41
102870.....	48	126	4045312	41
103773.....	48	231	17340928	30211
104731.....	48	440	4045824	41
104985.....	48	440	12712192	41
105912.....	48	355	17345280	30211
109756.....	48	231	17342208	30211
110897.....	48	755	4046080	41
111395.....	48	755	4046336	41
111545.....	48	355	17344768	30211
112164.....	48	440	4046592	41
114613.....	48	355	4046848	41
114710.....	48	126	4047104	41
114729.....	48	1510	4084480	41
114783.....	48	2181	4055552	41
115383.....	48	231	4047360	41
115617.....	0	1321	12712960	41
115617.....	48	126	4047616	41
117043.....	48	1007	4047872	41
117176.....	0	440	12716800	41
117176.....	48	126	4048128	41
118972.....	48	440	4048384	41
120005.....	48	107	17339648	30211
120136.....	48	126	4048640	41
120690.....	48	1090	4048896	41

TABLE 2—Continued

NAME (HD)	INTEGRATION TIME (s)		AOR KEY ^a	PID
	24 μm	70 μm		
122862.....	48	545	4049152	41
123691.....	48	355	17344512	30211
126660.....	48	126	4006912	41
127334.....	48	1007	4049408	41
128311.....	0	1090	4083456	41
128311.....	48	2181	8776192	41
130460.....	48	355	17347584	30211
130948.....	48	440	4049664	41
133002.....	48	440	4049920	41
134083.....	48	231	4050176	41
134987.....	48	1090	4050432	41
136064.....	48	231	4050688	41
136118.....	92	2181	12712448	41
141128.....	48	355	17345792	30211
142373.....	48	126	4050944	41
142860.....	48	126	4051200	41
143105.....	48	132	17340160	30211
143761.....	48	355	4051456	41
145675.....	48	1007	4051712	41
146233.....	48	231	4081664	41
149661.....	48	126	4051968	41
152391.....	48	1300	4061440	41
154088.....	48	1300	4061696	41
157214.....	48	231	4007168	41
160691.....	48	126	4061952	41
166620.....	48	231	4052224	41
168151.....	48	355	4052480	41
168443.....	48	126	4052736	41
169830.....	48	545	4063488	41
171886.....	48	355	17346048	30211
173667.....	48	126	4052992	41
176441.....	48	355	17339392	30211
177830.....	48	2181	4053248	41
181321.....	48	1300	4062208	41
181655.....	48	755	4053504	41
185144.....	48	126	4053760	41
186408.....	48	755	4054016	41
186427.....	48	755	4054016	41
188376.....	48	126	4054272	41
189567.....	48	545	4054528	41
190007.....	48	1007	4082432	41
190248.....	48	126	4054784	41
191408.....	48	126	4055040	41
193664.....	48	440	4055296	41
196050.....	48	2181	12711424	41
196378.....	48	231	4055808	41
196761.....	48	881	4056064	41
197692.....	48	126	4056320	41
200433.....	48	231	17343744	30211
202884.....	48	355	17347328	30211
203608.....	48	126	4056576	41
206860.....	48	650	4056832	41
207129.....	48	126	4057088	41
209100.....	48	126	4057344	41
210277.....	48	1950	4057600	41
210302.....	48	231	4057856	41
210918.....	48	755	4058112	41
212330.....	48	231	4058368	41
212695.....	48	231	17343488	30211
213240.....	0	355	4080896	41
213240.....	48	2181	8776448	41
216345.....	48	881	12712704	41
216437.....	48	545	4083968	41

TABLE 2—Continued

NAME (HD)	INTEGRATION TIME (s)		AOR KEY ^a	PID
	24 μm	70 μm		
216803.....	48	440	4058624	41
217014.....	48	231	4058880	41
217813.....	48	1510	4062464	41
219134.....	48	231	4059392	41
219983.....	48	107	17339904	30211
220182.....	48	1007	4062720	41
221420.....	48	440	4059648	41
222143.....	48	1090	4059904	41
222368.....	48	231	4060160	41
222404.....	48	231	12710912	41
222582.....	92	2181	4005888	41
225239.....	48	650	4060416	41

NOTE.—HD 10647 was observed in PID 717, a MIPS in-orbit check-out (IOC) program.

^a Further details of each observation, including pointing and time and date of observation, can be queried from the *Spitzer* Data Archive at the *Spitzer* Science Center using the specified AOR key.

The 24 μm centroid positions, which are consistent with the telescope pointing accuracy of $<1''$ (Werner et al. 2004), are used as the target coordinates for both wavelengths. The only significant update from previous papers is a 4% increase in the overall calibration at 70 μm from 15.8 to 16.5 mJy arcsec⁻²/MIPS_70_unit.

4. PHOTOSPHERIC PREDICTIONS AND DETECTIONS OF EXCESS

4.1. 24 μm

To determine whether any of our target stars have an IR excess, we compare the measured photometry (F) to predicted photospheric levels (P). High quality K magnitudes are required to extrapolate to 24 μm . Most of our stars have good 2MASS photometry (Skrutskie et al. 2006), but stars brighter than $m_K \sim 4.5$ saturate in 2MASS and therefore this survey cannot provide accurate photometry. We obtained photometry for as many of these “non-2MASS” stars as possible from the literature, and transformed it to the 2MASS system according to relations in Bessell et al. (1998) and Carpenter (2001). The errors for some of this “heritage photometry” are difficult to estimate, since infrared photometric systems were still under evolution when some of it was obtained. We show below that the net errors after transformation are surprisingly small. For 16 additional stars where we could find no K -band photometry, we estimated values from $B - I$ or $B - V$ colors. We obtained the optical colors from SIMBAD for the members of our sample and carried out linear fits against $I - K$ or $V - K$. The rms scatter around the fit was 0.07 for $B - I$ versus $I - K$ and 0.09 for $B - V$ versus $V - K$, and we take this scatter to be the error in the estimated K and K_s magnitudes. There are 12 stars for which we were unable to make even estimates of K and K_s magnitudes.

For the 181 sources where K_s data is available, we use the following approach. We computed ratios of the measured flux densities at 24 μm and K_s to determine the mean photospheric color. There is a weak dependence of this photospheric color on spectral type. We calculated this correction by assigning a numerical value proportional to spectral type (0 for A0, 10 for F0, 15 for F5, etc.) and multiplying the ratios by $1.048/(1+0.048^*$

TABLE 3
PHOTOSPHERIC PREDICTIONS AND PHOTOMETRY FOR ALL SOURCES

Name (HD)	V (mag)	K (mag)	$F24$ (mJy)	$P24$ (mJy)	$R24$	$F70$ (mJy)	σ_{70} (mJy)	$P70$ (mJy)	χ_{70}
63.....	7.13	6.01	29	28	1.02	6	3	3	0.86
142.....	5.70	4.47	122	117	1.05	28	6	13	2.60
166.....	6.07	4.31	158	138	1.15	104	4	15	22.57
693.....	4.89	3.61 ^{7b}	255	252	1.01	39	4	28	2.95
1237.....	6.59	4.86	82	83	1.00	11	2	9	0.89
1539.....	7.03	5.82	34	33	1.01	-0.1	3	4	-1.19
1581.....	4.23	2.77	546	558	0.98	84	6	60	4.06
3126.....	6.9	5.75	41	35	1.16	108	3	4	35.58
3296.....	6.72	5.59	42	41	1.02	24	3	5	6.81
3302.....	5.51	4.50	120	112	1.07	10	5	13	-0.63
3651.....	5.88	4.00	191	184	1.04	16	6	21	-0.92
3795.....	6.14	4.33	135	133	1.01	19	2	15	1.60
3823.....	5.89	4.49	114	115	0.99	14	4	13	0.22
3861.....	6.52	5.28	54	55	0.98	4	3	6	-0.54
4307.....	6.15	4.62	101	102	0.99	10	4	11	-0.28
4628.....	5.74	3.566 ^c	278	275	1.01	26	10	31	-0.44
7570 ^d	4.97	3.50 ^d	255	284	0.90	44	7	28	2.46
8070.....	6.65	5.61	39	40	0.97	2	3	4	-0.92
8574.....	7.12	5.78	34	35	0.98	3	2	4	-0.44
9826.....	4.10	2.86	527	513	1.03	55	5	58	-0.64
10476.....	5.24	3.24 ^c	360	371	0.97	53	8	40	1.70
10647.....	5.52	4.17 ^f	187	154	1.21	859	6	17	136.40
10697.....	6.27	4.60	100	105	0.95	1	5	11	-2.11
10800.....	5.88	4.41	124	125	1.00	14	3	14	-0.01
13445.....	6.12	4.13	163	164	0.99	5	7	18	-1.79
13555.....	5.23	4.12	167	160	1.05	19	5	18	0.26
14412.....	6.33	4.55	112	110	1.02	14	2	12	0.97
14802.....	5.19	3.68 ^d	259	242	1.07	36	6	28	1.15
15335.....	5.89	4.48	120	116	1.04	8	4	13	-1.21
15798.....	4.74	3.56 ^b	267	267	1.00	22	5	29	-1.49
16160.....	5.79	3.44 ^g	311	311	1.00	35	6	34	0.28
17051.....	5.40	4.14	167	159	1.05	22	3	18	1.34
17925.....	6.05	4.02 ^c	191	182	1.05	71	5	21	9.14
19373.....	4.05	2.65 ^c	626	626	1.00	57	7	69	-1.59
19994.....	5.07	...	241	...	...	43	4	26	4.25
20367.....	6.40	5.04	67	69	0.97	9	4	7	0.56
20630.....	4.84	3.24 ^h	355	366	0.97	42	7	39	0.43
20766.....	5.53	3.99 ^d	189	183	1.03	30	4	21	2.16
20807.....	5.24	3.77 ^d	233	223	1.05	46	4	26	5.44
22484.....	4.29	2.88 ^c	514	504	1.02	108	5	56	9.58
23079.....	7.12	5.71	37	37	0.98	5	1	4	0.95
23596.....	7.25	5.87	33	32	1.02	4	4	4	0.058
26923.....	6.32	4.90	76	78	0.97	7	3	8	-0.57
27442.....	4.44	1.93 ^j	1148	1248	0.92	136	5	126	1.82
28185.....	7.80	6.19	23	24	0.94	1	5	3	-0.31
30495.....	5.49	4.00	191	181	1.06	116	4	21	26.58
30652.....	3.19	2.05 ^g	1060	1071	0.99	118	5	116	0.38
33262.....	4.71	3.39 ^d	325	315	1.03	61	5	36	4.83
33564.....	5.08	3.91	185	194	0.95	25	5	20	1.00
33636.....	7.00	5.57	42	42	0.99	35	2	5	13.81
34411.....	4.69	3.24 ^c	363	363	1.00	40	10	40	0.05
34721.....	5.96	4.56	109	108	1.01	6	3	12	-1.81
35296.....	5.00	3.67 ^f	238	243	0.98	31	6	26	0.67
37394.....	6.21	4.27	139	143	0.97	30	6	15	2.42
39091.....	5.65	4.24	139	145	0.96	23	3	15	2.69
40979.....	6.74	5.45	47	47	1.00	14	6	5	1.50
43162.....	6.37	4.73	94	93	1.01	15	2	10	2.19
43834.....	5.08	3.40 ^d	309	316	0.98	44	11	34	0.95
50554.....	6.84	5.47	46	46	1.00	42	4	5	9.29
50692.....	5.74	4.29	136	138	0.99	12	11	15	-0.28
52265.....	6.29	4.95	74	75	0.98	38	5	8	5.63
52711.....	5.93	4.54	116	111	1.05	14	4	13	0.24
55575.....	5.54	4.12	166	162	1.02	30	4	18	2.91
57703.....	6.78	5.69	38	37	1.02	37	3	4	9.67

TABLE 3—Continued

Name (HD)	<i>V</i> (mag)	<i>K</i> (mag)	<i>F</i> 24 (mJy)	<i>P</i> 24 (mJy)	<i>R</i> 24	<i>F</i> 70 (mJy)	σ_{70} (mJy)	<i>P</i> 70 (mJy)	χ_{70}
58855.....	5.35	4.18	153	152	1.01	14	3	17	−0.85
60912.....	6.89	5.81	35	34	1.03	3	3	4	−0.15
62613.....	6.55	4.86	83	83	1.00	11	3	9	0.53
63333.....	7.09	5.79	35	34	1.01	0.1	3	4	−1.19
68456.....	4.74	3.62 ^d	256	254	1.01	31	5	28	0.59
69830.....	5.95	4.17	232	158	1.47	26	3	17	2.82
69897.....	5.13	...	196	...	...	32	5	22	2.18
70843.....	7.06	5.869	32	32	1.01	9	7	4	0.78
71148.....	6.32	4.83	81	85	0.96	4	3	9	−2.11
71640.....	7.4	6.01	29	28	1.02	−0.7	2	3	−1.53
72905.....	5.63	4.17	164	154	1.06	42	3	18	7.71
75616.....	6.92	5.68	39	38	1.03	41	2	4	16.01
75732.....	5.96	4.02	172	181	0.95	21	4	19	0.46
76151.....	6.01	4.46	123	119	1.03	33	3	14	5.51
77967.....	6.61	5.42	48	48	1.00	2	4	5	−0.91
79392.....	6.75	5.76	37	35	1.05	3	3	4	−0.21
80218.....	6.61	5.31	53	54	0.98	6	8	6	0.04
82943.....	6.54	5.11	66	65	1.02	119	5	7	24.91
83451.....	7.12	5.76	35	35	1.01	1	3	4	−0.86
83525.....	6.9	5.65	38	39	0.99	8	3	4	1.42
84117.....	4.93	3.54 ^d	246	275	0.89	16	11	27	−0.9
84737.....	5.08	3.61	250	258	0.97	34	4	27	1.60
86147.....	6.7	5.58	42	41	1.00	−1	3	5	−1.78
88230.....	6.60	3.17 ^{cgkl}	428	396	1.08	39	4	47	−2.07
88984.....	7.3	6.06	27	27	1.00	−0.8	7	3	−0.54
90839.....	4.82	3.52 ^d	283	279	1.02	34	4	31	0.85
93081.....	7.09	5.91	31	31	1.00	9	3	3	2.02
94388.....	5.23	...	171	...	...	18	3	19	0.26
95128.....	5.03	...	268	...	...	32	4	29	0.67
99126.....	6.94	5.62	39	40	0.97	0.9	3	4	−1.24
100067.....	7.17	5.89	30	31	0.96	−6	2	3	−4.43
101259.....	6.40	4.48	148	118	1.25	21	3	13	3.33
101501.....	5.31	3.56 ^c	262	276	0.95	29	4	29	0.10
102438.....	6.48	4.80	85	87	0.98	12	4	9	0.82
102870.....	3.59	2.29 ^j	886	869	1.02	117	9	97	2.11
103773.....	6.73	5.62	40	40	1.00	1	3	4	−1.14
104731.....	5.15	4.09	171	165	1.04	5	7	19	−2.00
104985.....	5.78	...	351	...	...	37	4	39	−0.4
105912.....	6.95	5.91	47	31	1.53	32	2	3	11.97
109756.....	6.95	5.75	37	35	1.04	13	3	4	2.47
110897.....	5.95	4.47	115	117	0.98	56	4	13	11.56
111395.....	6.29	4.65	97	101	0.96	14	3	11	0.93
111545.....	6.99	5.90	31	31	1.00	4	2	3	0.29
112164.....	5.89	4.48	114	116	0.98	15	18	13	0.13
114613.....	4.85	3.23 ^j	366	370	0.99	55	5	40	2.63
114710.....	4.23	2.85 ^{egkm}	507	517	0.98	47	6	56	−1.57
114729.....	6.68	5.14	62	64	0.98	10	3	7	1.17
114783.....	7.56	5.48	45	47	0.95	6	4	5	0.34
115383.....	5.19	...	216	...	...	19	6	24	−0.79
115617.....	4.74	3.06 ^d	449	433	1.04	195	8	49	18.31
117043.....	6.50	4.80	84	88	0.96	15	3	9	1.76
117176.....	4.97	3.20 ^c	372	380	0.98	72	4	41	7.33
118972.....	6.92	4.93	85	78	1.08	33	3	9	6.96
120005.....	6.51	5.23	57	57	0.99	8	3	6	0.59
120136.....	4.50	3.31 ^d	338	338	1.00	34	6	37	−0.56
120690.....	6.43	4.67	100	99	1.01	8	3	11	−0.94
122862.....	6.02	4.58	105	106	0.99	16	3	12	1.23
123691.....	6.8	5.86	33	32	1.03	7	2	4	1.59
126660.....	4.04	2.83 ^d	574	526	1.09	65	7	63	0.32
127334.....	6.36	4.73	88	92	0.95	10	2	10	−0.15
128311.....	7.48	5.14	60	64	0.93	21	3	7	4.29
130460.....	7.22	6.05	27	27	1.02	5	3	3	0.58
130948.....	5.86	4.46	117	119	0.98	9	3	13	−1.41
133002.....	5.63	3.92	201	193	1.04	23	2	22	0.59
134083.....	4.93	3.86 ^f	203	203	1.00	34	6	22	2.02

TABLE 3—Continued

Name (HD)	<i>V</i> (mag)	<i>K</i> (mag)	<i>F</i> 24 (mJy)	<i>P</i> 24 (mJy)	<i>R</i> 24	<i>F</i> 70 (mJy)	σ_{70} (mJy)	<i>P</i> 70 (mJy)	χ_{70}
134987.....	6.47	4.88	76	81	0.94	4	8	8	-0.63
136064.....	5.15	...	207	...	...	21	5	23	-0.34
136118.....	6.93	5.60	39	41	0.94	3	3	4	-0.57
141128.....	7	5.93	30	30	1.00	8	3	3	1.73
142373.....	4.60	3.06 ^m	420	429	0.98	41	5	46	-0.96
142860.....	3.85	2.62 ^j	639	639	1.00	72	16	70	0.08
143105.....	6.76	5.52	44	44	1.00	7	3	5	0.84
143761.....	5.39	3.86	199	205	0.97	31	5	22	1.77
145675.....	6.61	4.71	92	95	0.96	11	2	10	0.03
146233.....	5.49	...	182	...	...	22	7	20	0.29
149661.....	5.77	3.85 ^l	211	213	0.99	31	6	23	1.33
152391.....	6.65	4.84	81	85	0.95	14	4	9	1.32
154088.....	6.59	4.76	87	91	0.96	2	7	10	-1.25
157214.....	5.38	3.82 ⁿ	216	214	1.01	25	4	24	0.24
160691.....	5.12	3.52 ^d	268	282	0.95	31	8	29	0.15
166620.....	6.38	4.23	146	149	0.98	7	4	16	-2.51
168151.....	4.99	...	208	...	...	23	3	23	0.07
168443.....	6.92	5.21	55	60	0.92	9	29	6	0.10
169830.....	5.90	4.69	98	95	1.03	10	7	11	-0.16
171886.....	7.16	5.98	29	29	0.99	0.8	2	3	-1.24
173667.....	4.19	3.02 ^d	442	439	1.01	69	7	49	2.93
176441.....	7.06	5.89	33	31	1.05	-5	3	4	-2.72
177830.....	7.18	4.81	88	87	1.01	6	3	10	-1.06
181321.....	6.48	4.93	80	78	1.03	4	6	9	-0.85
181655.....	6.29	4.68	92	98	0.94	7	3	10	-0.94
185144.....	4.67	2.74 ^c	567	591	0.96	71	5	62	1.79
186408.....	5.96	4.43	114	110	1.03	11	6	14	-0.61
186427.....	6.25	4.65	95	100	0.95	-1	5	10	-2.53
188376.....	4.70	2.95 ^d	515	477	1.08	51	11	57	-0.50
189567.....	6.07	4.51	110	113	0.98	19	3	12	1.90
190007.....	7.46	4.80	88	89	0.99	7	4	10	-0.66
190248.....	3.55	1.91 ^p	1262	1250	1.01	138	5	139	-0.08
191408.....	5.32	3.23 ^d	464	378	1.23	49	10	51	-0.19
193664.....	5.91	4.45	118	120	0.98	19	4	13	1.48
196050.....	7.50	6.03	26	28	0.95	2	3	3	-0.44
196378.....	5.11	...	229	...	...	32	3	25	1.97
196761.....	6.36	4.60	102	106	0.97	8	4	11	-0.85
197692.....	4.13	3.07 ^d	413	422	0.98	42	8	45	-0.50
200433.....	6.91	5.85	33	32	1.02	6	3	4	0.91
202884.....	7.27	6.03	28	28	1.03	8	2	3	2.03
203608.....	4.21	2.88 ^p	497	502	0.99	45	5	55	-1.88
206860.....	5.96	4.56	111	108	1.03	28	2	12	6.63
207129.....	5.57	...	164	...	...	289	11	18	24.6
209100.....	4.69	2.14 ^q	1039	1029	1.01	113	6	114	-0.23
210277.....	6.54	4.80	83	86	0.97	8	2	9	-0.55
210302.....	4.94	...	215	...	...	11	6	24	-2.1
210918.....	6.23	4.66	98	99	0.99	9	3	11	-0.65

TABLE 3—*Continued*

Name (HD)	V (mag)	K (mag)	$F24$ (mJy)	$P24$ (mJy)	$R24$	$F70$ (mJy)	σ_{70} (mJy)	$P70$ (mJy)	χ_{70}
212330.....	5.31	3.72 ^d	241	234	1.03	29	4	26	0.71
212695.....	6.94	5.82	33	33	0.99	38	3	4	11.59
213240.....	6.81	5.35	50	52	0.96	7	2	5	0.55
216345.....	8.08	7.97	5	5	0.98	3	4	1	0.65
216437.....	6.04	4.52	107	112	0.96	7	5	12	-0.98
216803.....	6.48	3.90 ^d	220	204	1.08	27	4	24	0.94
217014.....	5.45	3.91	189	197	0.96	27	4	21	1.36
217813.....	6.65	5.15	60	63	0.95	4	5	7	-0.52
219134.....	5.57	3.17 ^e	399	399	1.00	20	10	44	-2.51
219983.....	6.64	5.34	51	52	0.99	8	3	6	0.58
220182.....	7.36	5.47	46	48	0.96	5	3	5	0.05
221420.....	5.82	4.31	135	136	0.99	19	3	15	1.24
222143.....	6.58	5.08	67	68	0.99	7	2	7	-0.39
222368.....	4.13	2.9 ^f	517	493	1.05	60	7	57	0.40
222404.....	3.21	0.90 ^d	3551	3219	1.10	355	5	362	-1.4
222582.....	7.68	6.17	24	24	0.96	9	2	3	2.73
225239.....	6.10	4.44	126	121	1.04	10	4	14	-0.89

NOTES.— V magnitudes are from *Hipparcos*, with typical errors 0.01 mag (Perryman et al. 1997). Except as indicated, K magnitudes are from 2MASS, with typical errors 0.02 mag (Skrutskie et al. 2006). All of these sources are strongly detected at 24 μm , with intrinsically large S/N. We calculate $P70$ as $F24/9.10$, except for the six cases with 24 μm excesses and $P24$ (see text), where we calculate $P70 = P24/9.10$. For HD 207129, a seventh star with 24 μm excess, we identify the excess through Kurucz fitting; see text. The implied excess for HD 191408 is spurious (see text). There are 12 stars for which K -band data is not available, and therefore no $P24$ or $R24$ determinations. However, even for these stars, we can still find $P70$ as $F24/9.10$, and measure χ_{70} . For these 12 stars, χ_{70} is actually a lower limit, since there could be small 24 μm excesses that we cannot measure.

^a Beichman et al. (2006a) found that this system has a weak excess in the 30–34 μm region that is not evident in our 24 or 70 μm data.

^b McGregor (1994).

^c Johnson et al. (1968).

^d Derived from $B - I$.

^e Alonso et al. (1994).

^f Derived from $B - V$.

^g Glass (1975).

^h Bouchet et al. (1991).

^j Johnson et al. (1966).

^k Veeder (1974).

^l Persson et al. (1977).

^m Alonso et al. (1998).

ⁿ Carney & Aaronson (1979).

^p Glass (1974).

^q Mould & Hyland (1976).

^r Haas & Leinert (1990).

(type/22)), determined from a linear fit to the data. This procedure results in a predicted 24 μm flux ($P24$) for each of these 181 stars.

We then calculate the excess ratios ($R24 = F24/P24$) for each system (Table 3). The distribution of derived excess ratios is shown in Figure 5. The $R24$ distribution for all stars with K_s magnitudes (2MASS or heritage) is quite regular, with clear peak near unity. For $0.92 \leq R24 \leq 1.08$, the mean and median both have a value of 0.995, with an rms scatter of 0.032. For only the stars with heritage photometry, the analogous average is 0.997, the rms scatter is 0.031, and the median is 0.999. That is, there is no evidence for any systematic difference in the sources of K photometry and we can treat all stars measured in this way identically. We can therefore set a 3 σ threshold for identification of an excess. Our approach is the same that we took in Su et al. (2006). We take 1 σ to be the rms scatter value of 0.032. Our result of zero sources with $R24 < 0.92$ is consistent with this value of σ . We therefore set the 3 σ excess threshold to be 1.10. One star (HD 222404) has $R24 = 1.10$, and we consider this marginal case explicitly in the next paragraph. The next smallest $R24$ value above our 3 σ threshold is 1.15 (close to 5 σ), and six stars have even larger $R24$ values. The stars with 2MASS K_s magnitudes or heritage K magnitudes and excesses at 24 μm are HD 166, 3126, 69830, and 105912.

The stars with possible excesses based on estimated K magnitudes need to be discussed individually because of their larger K magnitude uncertainties. HD 10647 has $R24$ of 1.21, based on extrapolation from $B - V$, and hence at a level of $\sim 2.5 \sigma$. It has a very large excess at 70 μm , by more than a factor of 10 over the photosphere, and Chen et al. (2006) find an excess at 30–34 μm , so we consider the excess at 24 μm to be confirmed at the longer wavelengths. HD 101259 has an indicated excess ratio of 1.25, based on extrapolation from $B - V$, and hence at nearly 3 σ . It is not saturated in the 2MASS data at J , and if we apply the standard $J - K$ color for its spectral type, we estimate an excess ratio of 1.15. It has a modest but significant excess at 70 μm , so we accept the reality of the indicated one at 24 μm . HD 191408 has a ratio of 1.23, based on an estimate from $B - I$ and hence at a level of $\sim 3 \sigma$. It has no significant excess at 70 μm , with a 2 σ upper limit to the excess ratio of 1.7. We used Kurucz model fitting to make an independent prediction of the 24 μm flux density, and found an excess ratio of only 1.08, suggesting that our extrapolation is in error, probably due to a bad photometric point. Furthermore, IRS spectra throughout this region are photospheric (no excess; Beichman et al. 2006a). It is therefore unlikely that the possible 24 μm excess is real. HD 222404 has an excess ratio of 1.10 based on a K magnitude estimated from $B - I$, and hence at

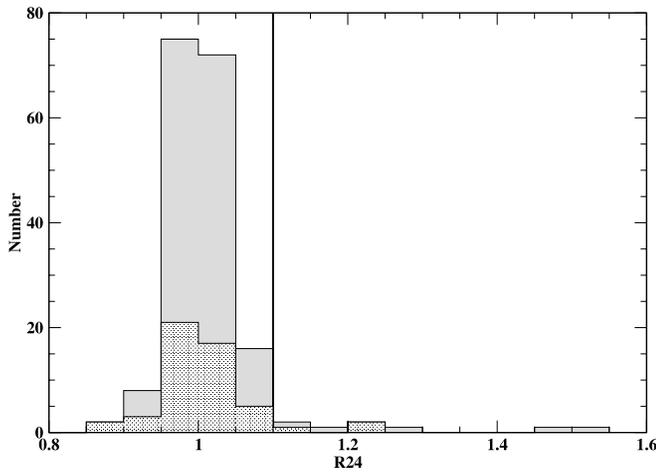


FIG. 5.—Histogram of R_{24} values, as described in the text. The shaded histogram shows the total number of stars in each bin, while the dotted region shows the subset for which K magnitudes are not derived from 2MASS. There is no systematic effect of using K magnitudes from other sources. The vertical line at 1.10 shows our excess threshold, as defined in the text. The core of this distribution is symmetric about unity. Seven systems have R_{24} values greater than 1.10; one of these is spurious, but the others are real excesses. See text for discussion.

a level of 1.5σ . However, the 2σ upper limit to the excess ratio at $70\mu\text{m}$ is only 1.04, so we reject the possibility of an excess at $24\mu\text{m}$. The remaining stars with estimated K magnitudes all have excess ratios < 1.10 . In summary, we therefore find six stars in the sample of stars with K magnitudes (2MASS, heritage, or estimated) with significant $24\mu\text{m}$ excesses (Table 5): HD 166, 3126, 10647, 69830, 101259, and 105912.

This “self-calibration” technique (using the data to define the outliers) is generally required in determining intrinsic stellar colors. For extreme outliers (Fig. 5), there is no question of the veracity of this technique. Furthermore, because the distribution of R_{24} is well behaved, with very small scatter, we are confident that it robustly reflects the true distribution of excesses. We further note that there is no procedure other than self calibration that works. There is no sample of stars measured at $24\mu\text{m}$ that includes the relevant spectral types and that is certain to have no small excesses. Kurucz model fitting leaves a small residual that must be removed empirically (Su et al. 2006). We checked our results using model fitting for a subset of targets and found agreement with the photometry-based extrapolations performed for the entire sample. Finally, we note that the rms scatter in the distribution of R_{24} is 0.02–0.023 from the K -band photometry, 0.01 from the $24\mu\text{m}$ photometry, and about 0.01 from the color-color relationships. Assuming these errors add quadratically (they are independent errors), the error left for variations in stellar color is 0.019, a very small number. This leaves little room for significant excesses for the bulk of the stars. We conclude that our self calibration technique is robust.

4.2. $70\mu\text{m}$

Since the majority of the stars in our sample do not have $24\mu\text{m}$ excesses, in general we make our $70\mu\text{m}$ photospheric predictions based on the $24\mu\text{m}$ flux measurements. For stars with no excess emission, the expected F_{24}/F_{70} ratio is 9.10 (scaling by λ^2 and using the effective wavelengths specified above), so we derive predicted $70\mu\text{m}$ fluxes by dividing the observed $24\mu\text{m}$ fluxes by this numerical factor. The predicted fluxes (P_{70}) are listed in Table 3. Calculating P_{70} this way (and not from extrapolations from K magnitudes) allows us to capitalize on the

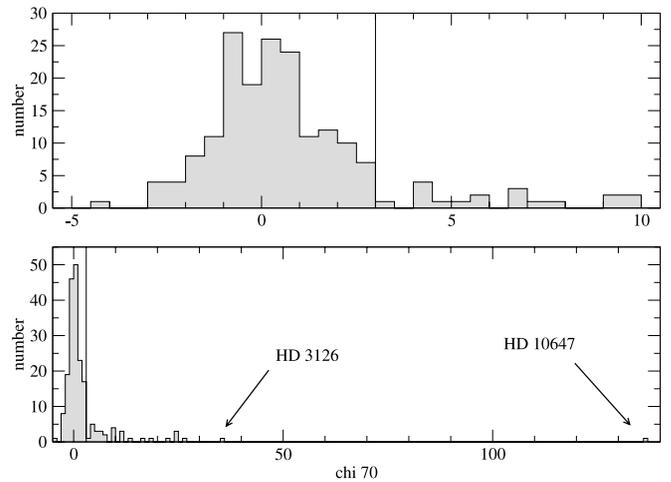


FIG. 6.—Distribution of χ_{70} values. The same data are presented in both panels. The top panel shows a smaller range in χ_{70} in order to show the shape of the core of the distribution. The bottom panel shows data for all 193 systems. Vertical lines in each panel show $\chi_{70} = 3.0$, our threshold criterion. The bin sizes in the two panels are not the same (0.5 and 1 in top and bottom, respectively). Two noteworthy systems are labeled in the bottom panel. The systems HD 19994 ($\chi_{70} = 4.25$) and HD 207129 ($\chi_{70} = 24.6$) are included in this figure. HD 100067 has a very low χ_{70} value of -4.43 , a result of a negative F_{70} value for this star, which means that this star was not detected. No stars that were detected have $\chi_{70} < -3.0$.

nearly uniform $24/70$ flux ratio rather than extrapolating from K and potentially magnifying any slight misestimates. It also allows us to determine P_{70} for the 12 stars that have no K -band measurements and therefore no P_{24} , so that we can search all 193 stars in our sample for $70\mu\text{m}$ excesses. Naturally, for the six stars with $24\mu\text{m}$ excess this extrapolation from observed $24\mu\text{m}$ fluxes to $70\mu\text{m}$ predictions does not work; for these systems, we extrapolate the predicted $24\mu\text{m}$ fluxes to derive predicted $70\mu\text{m}$ fluxes, using this same numerical factor of 9.10. For these six cases, our $70\mu\text{m}$ predictions are confirmed with Kurucz model fitting.

The large scatter and large number of (expected) excesses at $70\mu\text{m}$ makes determining the excess threshold in the circular manner above problematic. We instead quantify the significance of the (possible) $70\mu\text{m}$ excess χ_{70} , which is defined as follows:

$$\chi_{70} = \frac{F_{70} - P_{70}}{\sigma_{70}},$$

where F_{70} and P_{70} are as defined above and σ_{70} is the error in the measurement.

We use the same criterion as Su et al. (2006) to identify significant excesses: we require $\chi_{70} \geq 3$. This is identical to saying that the significance of the excess must be at least 3σ . The distribution of χ_{70} is shown in Figure 6. The core of this distribution is clearly centered near zero, the expected value for a sample where nonexcess is the majority outcome. Nevertheless, the distribution of χ_{70} shown in the top panel of Figure 6 is not symmetric in the range $-3 < \chi_{70} < 3$: the broad shape of the right “shoulder” in the top panel of Figure 6 ($1.5 < \chi_{70} < 3$) suggests the presence of a number of low-level excesses (below our detection threshold).

In our large sample, we can test the reliability of these determinations by counting the number of stars that fall below our -3σ excess criteria (that is, $\chi_{70} \leq -3.0$). Only one star (HD 100067) has $\chi_{70} \leq -3.0$ (Fig. 6). This system has a large negative χ_{70}

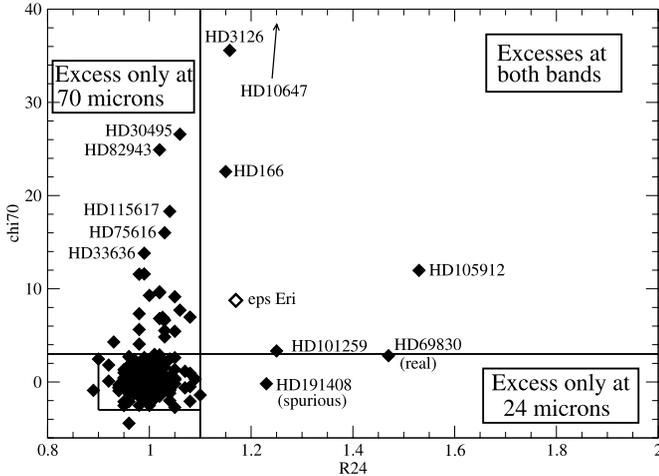


FIG. 7.— R_{24} and χ_{70} for the 181 stars with P_{24} (Table 3). The R_{24} and χ_{70} excess thresholds are shown by vertical and horizontal lines, respectively. The box in the bottom left shows the area enclosed by $(-3\sigma, 3\sigma)$ in the two dimensions. Targets within this box show the core of our sample, having no excess at either band. In addition to showing the distribution of our sources in this parameter space, we also confirm here that no obvious systematic effects arise from our technique for deriving P_{24} and P_{70} . Such a systematic error would be manifest as a correlation between R_{24} and χ_{70} in the (core) nonexcess sample (if the photospheric models were incorrect, for instance). Instead, we see that this core distribution is essentially a random scatter distribution (fully uncorrelated), confirming that our technique for predicting the 24 and 70 μm fluxes is appropriate. The regions with excesses at 24 μm only, 70 μm only, and at both bands are labeled. Targets with excesses at both bands are labeled (HD 10647 is off the plot to the top). HD 191408 clearly shows no excess at 70 μm , and we find that its 24 μm excess is spurious (see text). No other 24 μm excesses are spurious, since all of the rest have clear 70 μm excesses as well (excepting HD 69830, although the excess around that star is clear for many other reasons; see text). We also label the other five systems with the largest χ_{70} values; ϵ Eri (not observed as part of the programs presented here; see D. E. Backman et al., in preparation) is also plotted and labeled; it is clear that neither the 24 or 70 μm excesses for this famous debris disk are remarkably large. That star’s proximity (3.2 pc) accounts for its disk’s brightness and prominence.

value because the measured aperture photometry is formally negative (meaning the sky value subtracts more than the enclosed flux in the photometric aperture); in other words, this star was simply not detected at 70 μm (Table 3). There are no cases of $\chi_{70} < -3.0$ where the star is detected. Assuming symmetric noise properties, we therefore expect no spurious positive outliers.

In summary, we identify any system with $\chi_{70} \geq 3.0$ as an excess system. There are 27 such systems out of the 181 stars with K magnitudes. We define HD 69830 to have an excess at 70 μm because it has $\chi_{70} = 2.81$ and a significant (corroborating) excess at 24 μm ($R_{24} = 1.47$), bringing the number of systems with 70 μm excesses to 28 out of 181. This 28 includes six systems that have excesses at both 24 and 70 μm . Finally, 2 of the 12 stars with no K magnitudes also have 70 μm excesses (see § 5.3), based on $F_{24}/F_{70} < 9.10$. This brings the total number of systems with 70 μm excesses to 30 out of 193 (Table 3).

In Figure 7 we show the distribution of our 181 sources with K magnitudes in R_{24} - χ_{70} space. We confirm that there are likely no other spurious 24 μm excesses. Furthermore, the random scatter distribution (fully uncorrelated) of the nonexcess sources confirms that there are no systematic errors introduced by our technique of predicting 24 μm fluxes and extrapolating to predict 70 μm fluxes. Systems with weak excesses at both 24 and 70 μm would not necessarily be identified by the techniques we have described here. However, we see in Figure 7 that there are no systems in the upper right of the enclosed area, where such a system with two weak excesses would reside.

5. RESULTS

5.1. Excess Rates

There are 181 stars in our sample with well-constrained K -band magnitudes and therefore reliable 24 μm predicted fluxes. We can make excess determinations for all 193 stars at 70 μm (in most cases based on our 24 μm measurements). We add to this catalog three stars that meet the selection criteria for PID 41 but had already been included in other observing programs: ϵ Eri ($K2$ V, 3×10^8 yr); τ Ceti ($G8$ V, 7.2×10^9 yr); and τ^1 Eri ($F6$ V, 3×10^8 yr) (Table 3 from B06; Decin et al. 2003; Chen et al. 2006). The first of these has excesses at both 24 and 70 μm (D. E. Backman et al., in preparation); the second is photospheric at 24 μm and has an excess at 70 μm (Chen et al. 2006; Stapelfeldt et al. 2006); and the third has no excess at either 24 or 70 μm (Chen et al. 2006; Stapelfeldt et al. 2006; Trilling et al. 2007). These additions bring the total excess rates to the following values: at 24 μm , 7 out of 184 stars have excesses, giving $3.8^{+1.7}_{-1.2}\%$; and at 70 μm , 32 out of 196 stars have excesses, giving $16.3^{+2.9}_{-2.8}\%$. In all cases in this paper, we cite binomial errors that include 68% of the probability (equivalent to the 1σ range for Gaussian errors), as defined in Burgasser et al. (2003). All of the systems with 24 μm excesses also have 70 μm excesses. These excess rates are also presented in Table 4.

Of the 196 stars presented here in our FGK sample, 48 are known to harbor extrasolar planets. The excess rates for the planet sample are higher than the no-planet sample, although formally the two samples’ excess rates are consistent at the 1σ level (Table 4). Bryden et al. (2007) discuss further the differences for excess rates and debris disks for stars with and without known planets. Planets have been found around $\sim 10\%$ of the stars surveyed in radial velocity programs (Udry et al. 2007), but here planet-bearing stars represent 25% of the total FGK sample, so there is the potential for contamination of our derived excess rate for FGK stars. However, if we weight the planets and no-planets excess rates (Table 4) by 10% and 90%, respectively, we find that the resulting total excess rates are 3.9% (24 μm) and 15.6% (70 μm), hardly different from the overall excess rates derived above ($3.8^{+1.7}_{-1.2}\%$ and $16.3^{+2.9}_{-2.8}\%$, respectively). We conclude that any contamination must therefore be insignificant.

5.2. Dust Properties

We interpret the presence of excess thermal infrared flux as a signature of emission from dust grains. These dust grains are assumed to be produced relatively recently from collisions of asteroid-like bodies. (Dust grains in these systems have short lifetimes against radiation forces.) By constraining the properties of this dust, we can learn about the processes of planetary system formation in a large sample of FGK stars.

In general, we would like to fit the observed excesses to a blackbody to determine the temperature of the excess. For systems with excesses at both 24 and 70 μm this is relatively straightforward: we find the blackbody temperature that best fits the two observed excesses. These temperatures are given in Table 5. We scale this blackbody by the appropriate amount to fit the excess measurements. The ratio of this scaled blackbody’s integrated flux to the star’s integrated flux is the fractional luminosity (Table 5, Fig. 8).

Most stars in our sample that show excesses, however, have excesses only at 70 μm , which leaves dust temperatures relatively unconstrained. In these cases—excess flux at 70 μm , photospheric flux at 24 μm —we set the 24 μm “excess” to be equal to three times the error at 24 μm (which is dominated by the calibration uncertainty), and find the blackbody that best fits this “excess”

TABLE 4
SUMMARY OF EXCESS RATES

SAMPLE	24 μm		70 μm	
	Number	Excess Rate (%)	Number	Excess Rate (%)
A.....	30	7^{+3}_{-3}	27	26^{+10}_{-7}
FGK sample.....	184	$3.8^{+1.7}_{-1.2}$	196	$16.3^{+2.9}_{-2.8}$
FGK sample, planets.....	45	$6.7^{+5.8}_{-2.1}$	48	$20.8^{+7.0}_{-4.6}$
FGK sample, no planets.....	139	$2.9^{+2.2}_{-0.8}$	148	$14.9^{+3.4}_{-2.5}$
All F.....	110	$7.3^{+3.3}_{-1.2}$	117	$17.9^{+4.1}_{-3.0}$
All G.....	103	$1.0^{+2.2}_{-1.0}$	108	$14.8^{+4.0}_{-2.8}$
All K.....	51	$5.9^{+5.2}_{-1.8}$	51	$13.7^{+6.2}_{-3.5}$
M.....	62	$0.0 + 2.9$	13	$0.0 + 12$
Sun-like supersample (FG).....	213	$4.2^{+2.0}_{-1.1}$	225	$16.4^{+2.8}_{-2.9}$

NOTES.—The A stars sample includes stars with ages ≥ 600 Myr from Su et al. (2006). The FGK sample is all data presented in this paper, from PIDs 41 and 30211, plus the three additional stars listed in § 5.1. The “All F/G/K” samples are produced by combining data presented in this paper with data from Beichman et al. (2006b) for the given spectral types. The M stars results are taken directly from Gautier et al. (2007). The Sun-like supersample is defined in § 6.4 as all F and all G stars from this paper and from Beichman et al. (2006b) combined. In all of these samples, all stars that have excesses at 24 μm also have excesses at 70 μm (except some of the A stars, where only upper limits are available at 70 μm for some sources). In all cases in this paper, we cite binomial errors that include 68% of the probability (equivalent to the 1σ range for Gaussian errors), as defined in Burgasser et al. (2003).

and the measured 70 μm excess. This resulting temperature is the maximum temperature for the excess (Table 6).

After solving for this dust temperature (T_d), we can calculate the orbital distance r (in AU) of the dust through equation (3) from Backman & Paresce (1993):

$$r = \left(\frac{278}{T_d}\right)^2 \left(\frac{L_\star}{L_\odot}\right)^{0.5}, \quad (1)$$

TABLE 5
COLOR TEMPERATURE FOR EXCESSES DETECTED AT BOTH BANDS

Name (HD)	$F_{24\text{excess}}$ (mJy)	$F_{70\text{excess}}$ (mJy)	T_{dust} (K)	R_{dust} (AU)	f_d ($\times 10^{-5}$)
166.....	20	89	87	9.1	5.9
3126.....	6	104	66	21.8	13
10647 ^a	33	842	62	21	34
69830 ^b	74	9	1900	0.02	560
			400	1.0	20
101259.....	30	8	271	0.98	6.0
105912.....	16	29	110	7.7	7.9
207129 ^c	24	274	72	15.3	12

NOTES.— T_{dust} is found by fitting a blackbody to the measured excesses. This blackbody is then scaled to fit the observed fluxes, and the ratio of this scaled blackbody’s integrated flux to the star’s integrated flux gives the fractional luminosity (f_d). We solve for R_{dust} using eq. (1). ϵ Eri is not listed here, but does have excess at both bands (D. E. Backman et al., in preparation) and a planet orbiting it (Hatzes et al. 2000).

^a This star has a known planet orbiting at 2.03 AU (Butler et al. 2006).

^b The first line for HD 69830 here shows our naive solution for this system, based on the fluxes at 24 and 70 μm , and assuming that all of the flux arises from continuum emission. A dust grain temperature of nearly 2000 K is not sensible, however, as this is above the sublimation temperature for any reasonable dust composition. However, Beichman et al. (2005b) found that a significant fraction of the excess flux from this system appears in emission features, meaning that our continuum assumption overestimates the dust temperature (with consequences for dust distance and fractional luminosity). The second line for HD 69830 here shows the best values for these parameters from Beichman et al. (2005b) and Lisse et al. (2007) derived from more appropriate model fitting of the emission spectrum. This star has three planets orbiting within 0.65 AU (Lovis et al. 2006).

^c There is no good K magnitude available for this star, but Kurucz model fitting clearly indicates an excess at 24 μm . The excess at 70 μm is indicated by comparison to the Kurucz model and also by the ratio F_{24}/F_{70} .

where L_\star is the stellar luminosity. (Large grains with unit emissivities that radiate as black bodies are assumed.) We calculate the stellar luminosity of the host star simply through

$$L_\star = 4\pi R_\star^2 \int \text{Kurucz model} = 4\pi R_\star^2 \sigma T_{\text{eff}}^4, \quad (2)$$

where R_\star is the stellar radius (from Drilling & Landolt 2000) and the stellar effective temperature T_{eff} is given in Table 1 and again in Table 6. Our calculated dust distances are given in Tables 5 and 6 and Figure 8. For systems with excesses only at 70 μm , the

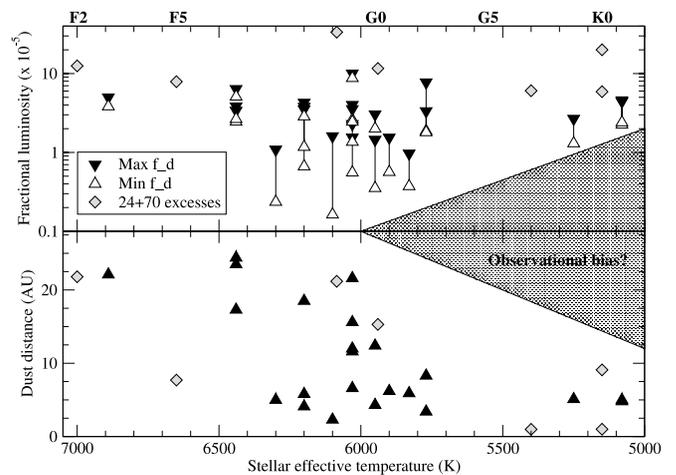


FIG. 8.—Derived fractional luminosities and dust distances as a function of stellar effective temperature (i.e., spectral type). We show maximum (downward triangles) and minimum (upward triangles) fractional luminosities, connected by vertical lines, in the top panel, and minimum dust distances (upward triangles) in the bottom panel. For the seven systems with excesses at both wavelengths we can solve for the fractional luminosity and dust distance exactly (not limits), so these values are shown as diamonds (green symbols). These seven systems have relatively high fractional luminosities. For HD 69830, we plot here the published values from Beichman et al. (2005b) and Lisse et al. (2007). As a point of comparison, our solar system’s asteroid belt resides at 3–5 AU, and our Kuiper Belt exists at 30–50 AU. The lack of excesses at large distances and small fractional luminosities around the latest stellar types may be an observational bias. [See the electronic edition of the Journal for a color version of this figure.]

TABLE 6
DUST PROPERTIES FOR SYSTEMS WITH EXCESS AT 70 μm ONLY

NAME (HD)	T_{eff} (K)	T_{dust} (K)	R_{dust} (AU)	$f_d (\times 10^{-5})$	
				Maximum	Minimum
1581.....	6100	218	2.3	1.6	0.2
3296.....	6440	89	17	3.8	2.5
17925.....	5080	103	4.8	4.4	2.2
19994 ^a	6200	168	4.1	3.5	0.7
20807.....	5950	150	4.3	1.5	0.4
22484.....	6200	142	5.8	4.3	1.2
30495.....	5950	88	12	3.0	2.0
33262.....	6300	158	5.0	1.1	0.2
33636 ^b	6030	81	16	3.5	2.6
50554 ^c	6200	79	19	3.8	2.9
52265 ^d	6030	92	12	4.0	2.4
57703.....	6890	78	22	5.0	3.8
72905 ^{de}	5900	123	6.2	1.5	0.6
75616.....	6440	77	24	3.4	2.6
76151 ^f	5830	120	5.9	1.0	0.4
82943 ^g	6030	69	22	10.0	8.8
110897.....	6030	94	12	2.3	1.4
115617.....	5770	97	8.3	3.3	1.9
117176 ^h	5770	153	3.4	7.7	1.8
118972.....	5080	101	5.0	4.6	2.4
128311 ^{jk}	5250	106	5.1	2.7	1.3
206860 ^l	6030	124	6.6	1.5	0.6
212695.....	6440	75	24	6.4	5.1

NOTES.—These dust temperatures are maximum temperatures, and the distances consequently are minimum distances. Both maximum and minimum fractional luminosity (f_d) values are given; the former corresponds to the dust temperatures and radii given in this table (see text), while the latter corresponds to 50 K dust temperature solutions. These two values give the range of fractional luminosities that fit the data (see Fig. 8).

^a This star has a known planet orbiting at 1.4 AU (Mayor et al. 2004).

^b This star has a known planet orbiting at 3.27 AU (Butler et al. 2006).

^c This star has a known planet orbiting at 2.28 AU (Butler et al. 2006).

^d This star has a known planet orbiting at 0.5 AU (Butler et al. 2006).

^e Beichman et al. (2006a) derive a fractional luminosity of 2.9×10^{-5} based on 70 μm photometry and IRS spectroscopy.

^f Beichman et al. (2006a) derive a fractional luminosity of 1.2×10^{-5} based on 70 μm photometry and IRS spectroscopy.

^g This star has two known planets orbiting at 0.752 and 1.19 AU (Mayor et al. 2004; Lee et al. 2006).

^h This star has a known planet orbiting at 0.484 AU (Butler et al. 2006).

^j Beichman et al. (2006a) found no excess for this star in IRS spectra out to 35 μm , but calculate a fractional luminosity of 2.6×10^{-5} based on 70 μm photometry (the same data that are presented here).

^k This star has two known planets orbiting at 1.10 and 1.76 AU (Vogt et al. 2005).

^l Beichman et al. (2006a) derive a fractional luminosity of 0.7×10^{-5} based on 70 μm photometry and IRS spectroscopy.

distances we derive are minimum distances, since the dust temperatures we derive are maximum temperatures. In all cases, we assume blackbody grains.

Finally, from our blackbody fits to the excesses we also derive the fractional luminosities: the ratios of dust luminosity to stellar luminosity. This quantity is also referred to as f_d and L_d/L_* . The fractional luminosities we derive are given in Tables 5 and 6 and Figure 8. As above, for systems with excesses only at 70 μm , these derived fractional luminosities are the maximum values that are consistent with the observed data. However, extremely massive cold outer disks, which could imply a larger fractional luminosity than the “maximum” values we present here, cannot be ruled out.

To place a reasonable lower limit on the fractional luminosity estimates for systems with excesses only at 70 μm , we follow the

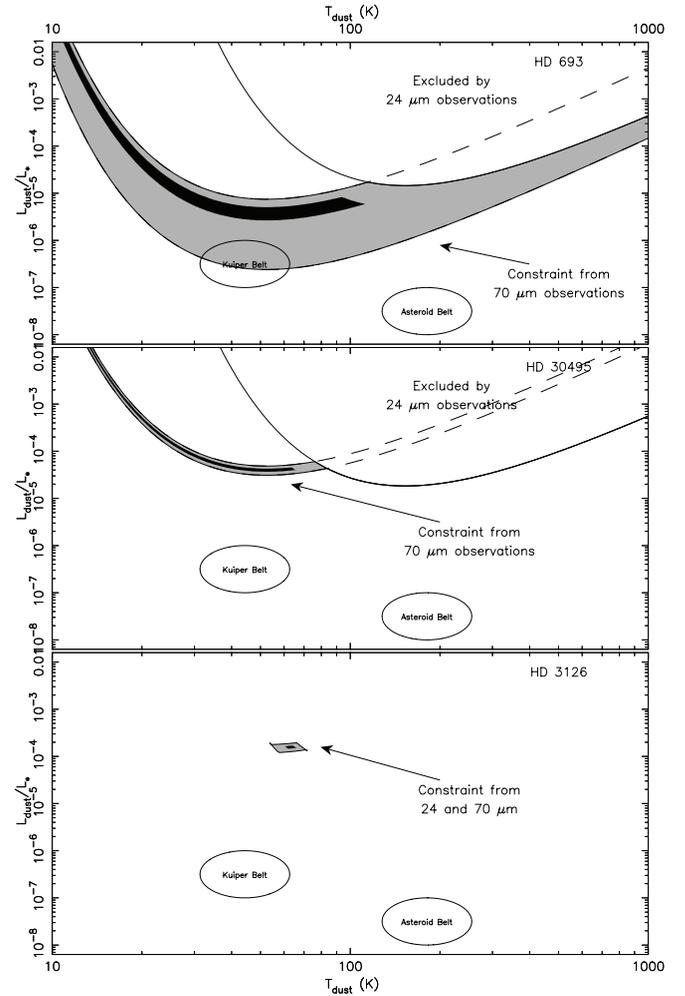


FIG. 9.—Range of possible fractional luminosities as a function of dust temperature for three noteworthy systems. The top right of each panel (hot, bright emission) is generally ruled out by our 24 μm measurements. Submillimeter observations could place limits on the top left of each panel (bright, cold emission). Based on the measured 70 μm excess, possible dust temperatures and luminosities are shown as shaded regions (gray for 3 σ error limits, black for 1 σ limits). The approximate characteristics of the asteroid and Kuiper belts are shown for comparison. The plausible range of dust properties for HD 693 overlaps with the properties of the dust in our Kuiper Belt (e.g., Teplitz et al. 1999). The dust properties for HD 3126 are well constrained due to its detection at both 24 and 70 μm .

arguments in B06 and Trilling et al. (2007) and assume a “minimum” possible disk temperature of 50 K. This assumption excludes the possibility that a very cold (and potentially massive) disk could exist, with significant emission at wavelengths longer than 70 μm . This 50 K blackbody is scaled to match the measured 70 μm excesses (this results in no detectable excess emission at 24 μm , consistent with the observations). We calculate the ratio of this disk’s luminosity to the stellar luminosity to derive the minimum fractional luminosities for systems with excesses at 70 μm only. We present these minimum disk luminosities in Table 6 and Figure 8. These two estimates of fractional luminosity give the range of values that fit the data. In many cases, the range of acceptable values is quite small. We see that the minimum fractional luminosity is around 10^{-5} , as has been found in other surveys as well (B06; Trilling et al. 2007).

5.3. Individual Systems of Interest

We describe here a few interesting individual cases, some of which are also shown in Figure 9, to demonstrate the range of disk properties evident in our sample.

HD 693.—This system has $\chi_{70} = 2.95$, just below our excess threshold. It is likely that there is a real excess in this system that is simply slightly too faint for us to detect formally. In addition, a massive and/or cold(er) disk cannot be ruled out. We identify this system as one of particular interest because of its low fractional luminosity: 3×10^{-6} (assuming that there is a real excess), which would make it comparable to some estimates of our solar system’s Kuiper Belt (Fig. 9). Also of note is its dust distance of 3.2 AU, clearly well within the realm of possible planetary systems.

HD 3126.—This star has a very large $70 \mu\text{m}$ excess ($\chi_{70} = 35.8$) and a modest $24 \mu\text{m}$ excess ($R_{24} = 1.16$). With an age of 3.5 Gyr and a SIMBAD spectral type of F2, there is nothing apparently anomalous about this system that could explain its large excess, i.e., the star is not young, nor is it evolved. (Favata et al. (1993) assign a spectral type of F4 V.) In Figure 9 we show the narrow range of possible fractional luminosities ($\sim 10^{-4}$) that are in accord with the observed data. The fractional luminosity is relatively high. This system is clearly promising for additional observations to better characterize the dust population.

HD 10647.—This star has a well-known infrared excess that was first detected with *IRAS* (Stencel & Backman 1991). Chen et al. (2006) determined a fractional luminosity of 15×10^{-5} for this system with *Spitzer* IRS measurements, using a temperature of 70 K. This is fairly consistent with the values we derive (Table 5), and is a relatively large fractional luminosity for the FGK sample we present here. HD 10647 is also known to harbor (at least) one extrasolar planet, orbiting at 2 AU (Butler et al. 2006). We find the dust to be at a distance of at least 21 AU (Table 5), although Jura et al. (2004) find an inner disk radius of 11 AU using IRS spectra and a warmer excess temperature than we find. This disk has also been detected in scattered light (K. R. Stapelfeldt et al., in preparation). This system is clearly fertile ground for further studies of planetary system formation, since both a giant planet and a large dust disk (and implied collisions among asteroidal bodies) are known to exist.

HD 19994.—There is no good *K* magnitude for this system, so we cannot determine whether it has a $24 \mu\text{m}$ excess. However, F_{24}/F_{70} is 5.6, making this system far too bright at $70 \mu\text{m}$ for the [24 : 70] color to be photospheric; we determine $\chi_{70} = 4.25$. This assumes that F_{24} is photospheric, which is the conservative assumption that makes our calculated χ_{70} a lower limit. Under this assumption, the maximum dust temperature is 170 K, the minimum dust distance is 4.1 AU, and the maximum fractional luminosity is 4×10^{-5} . These properties are similar to the other systems with excesses at $70 \mu\text{m}$ only.

HD 30495.—Among systems with no $24 \mu\text{m}$ excesses, HD 30495 has the most significant $70 \mu\text{m}$ excess ($\chi_{70} = 26.9$). These parameters suggest a relatively cool dust disk, as seen in Figure 9. As for HD 3126, a massive, cold disk cannot be ruled out.

HD 69830.—This system was discovered by Beichman et al. (2005b) to have substantial hot emission, which Lisse et al. (2007) attributed to the recent breakup of a large asteroid in that system. The excess infrared emission, evident from 8–35 μm (and, as we show here, marginally evident in photometry⁵ at $70 \mu\text{m}$), suggests quite high temperatures (~ 400 K) and a dust distance around 1 AU. This system further became interesting with the subsequent discovery of three Neptune mass planets in that system, all orbiting at less than 1 AU (Lovis et al. 2006).

HD 82943.—Among systems with excesses at $70 \mu\text{m}$ only, HD 82943 has the largest fractional luminosity, at more than 10^{-4} (Table 6). Moór et al. (2006) find that all systems with debris disk fractional luminosities greater than 5×10^{-4} are young. HD 82943 has an age of more than 4 Gyr (Table 1). Our fractional luminosity estimates for the disk around HD 82943 are below this apparent limit, so the age of more than 4 Gyr (Table 1) offers no direct contradiction. Nevertheless, this system may be useful in helping to define the exact border of the distribution discussed by Moór et al. (2006). (Other high fractional luminosity systems given in Tables 5 and 6 may also provide useful constraints.) We note that HD 82943 also has two planets orbiting it interior to 1.5 AU; these planets are locked in a 2 : 1 mean motion resonance (Mayor et al. 2004; Lee et al. 2006).

HD 101259.—We find an excess at both 24 and $70 \mu\text{m}$ for this star. Unusually, the excess in this system is not much brighter, relatively, at $70 \mu\text{m}$ than at $24 \mu\text{m}$ ($R_{24} = 1.25$ and $R_{70} = 1.61$). However, we note that both P_{24} and P_{70} for this system are based on the $B - V$ color, and therefore have a large uncertainty. Taken together, a small and warm excess is likely, but not certain. Follow-up observations will be critical in characterizing this system, and will be of particular interest since systems with warm dust are rare.

The measured excesses of $R_{24} = 1.25$ and $R_{70} = 1.61$ require a fairly warm disk temperature of 271 K, giving a dust distance of around 1 AU (Table 5). (The *IRAS* $12 \mu\text{m}$ flux also appears to be $\sim 25\%$ higher than the expected photospheric flux.) The properties of this disk appear quite similar to HD 69830 (see Fig. 7), and further observations (including IRS spectroscopy) should be made to characterize the dust population. In temperature and distance, the dust in this system closely resembles the zodiacal dust in our solar system, which is produced largely by collisions in the asteroid belt. The architecture of that planetesimal (and potential planet) system may not be that different from our own solar system’s.

HD 207129.—There is no good *K* magnitude measurement for this star, so we cannot predict its $24 \mu\text{m}$ fluxes. Nevertheless, this star has been known to have an infrared excess for more than 20 years (Aumann 1985), and has been studied with both *ISO* (Jourdain de Muizon et al. 1999) and in a number of ongoing *Spitzer* studies. The F_{24}/F_{70} ratio of 0.57 that we observe here is far from the photospheric value of 9.10 and clearly indicates a strong $70 \mu\text{m}$ excess and presence of a debris disk. We fit published visible and near-infrared data with a Kurucz model to predict the 24 and $70 \mu\text{m}$ fluxes (Fig. 10) and constrain the dust properties.

We find $P_{24} = 139$ mJy and $P_{70} = 15$ mJy. This gives excesses at 24 and $70 \mu\text{m}$ of 25 and 274 mJy, respectively. The fractional luminosity is around 10^{-4} , which is very high for a star like our Sun. The color temperature is 72 K, which, for this G0 star, gives R_{dust} of 15.3 AU. The temperature we derive is hotter than the *ISO*-derived range of 15–45 K, but our fractional luminosity agrees well with their values (Jourdain de Muizon et al. 1999). The properties we derive are similar to the other systems with excesses at both bands (Table 5). This debris disk ring has also been detected directly in scattered light (J. Krist et al., in preparation).

6. DISCUSSION

6.1. Metallicity and Excesses

Four stars in our FGK sample do not have published metallicities. For the 189 stars with known metallicities in Table 1, the mean metallicity is -0.08 ± 0.22 , with a median of -0.06 . The

⁵ The $70 \mu\text{m}$ flux reported here (26 mJy) is higher than that in Beichman et al. (2005b; 19 mJy) primarily due to better centering of the photometric aperture on the source. There is an additional small (5%) increase in the calibration factor that has been applied since Beichman et al. (2005b).

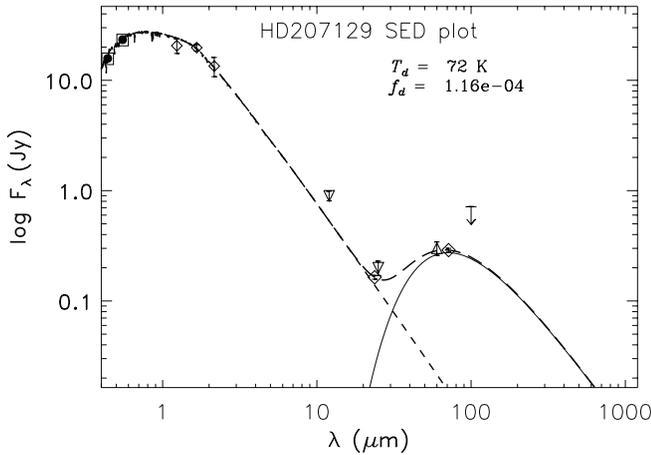


FIG. 10.—Spectral energy distribution (SED) for HD 207129. The total SED is shown by the dashed purple curve; the components are stellar (*black dashed line*) and dust (*solid black line*) emission. There is no good *K* magnitude for this star (the 2MASS *K*-band error is large), but we can find a satisfactory Kurucz fit, as shown. Visible (*Hipparcos*) and near infrared (2MASS) photometry are shown as blue circles and purple diamonds, respectively. *IRAS* measurements are shown as red symbols. Our MIPS photometry is shown as blue diamonds. We find an excess at both 24 and 70 μm and therefore derive the temperature and fractional luminosity given in the legend. The high *IRAS* 25 μm flux is due to another bright source $\sim 30''$ away. [See the electronic edition of the *Journal* for a color version of this figure.]

mean metallicity of stars with excesses is -0.11 ± 0.19 (median is -0.09). The mean metallicity of stars with no excesses is -0.08 ± 0.22 (median is -0.05). There is no difference between the metallicity of the population of stars with excesses and the population of stars with no excesses. This lack of correlation has been discussed previously (e.g., B06; Beichman et al. 2006b).

6.2. Excess Rates across Spectral Type

Many parameters affecting infrared excesses change with spectral type, including the importance of grain loss mechanisms (winds, Poynting-Robertson drag, photon pressure); stellar luminosity; and the locations of key temperatures (e.g., the ice line) in the systems. Significant surveys for debris disks across spectral types A–M have now been published, and we use those data to look for systematic trends across spectral types.

It is well known that excess rates decrease with stellar age (Habing et al. 2001; Spangler et al. 2001; Rieke et al. 2005; Su et al. 2006; Siegler et al. 2007). This dependence must be avoided in testing for changes with spectral type. We take the oldest (≥ 600 Myr) A stars from the Su et al. (2006) sample as our representative sample from that spectral type. For our F, G, and K samples we take the union of the data presented here and the data in Beichman et al. (2006b). The targets and data reduction presented in Beichman et al. (2006b) are quite similar to the selections and techniques we have employed here, which allows us to merge the two samples relatively seamlessly. We calculate the excess ratios for these F, G, and K samples and take the M stars excess rates from Gautier et al. (2007). This compilation is presented in Table 4 and Figure 11.

Within the error bars, the excess rates for the A, F, G, and K subsamples are essentially indistinguishable. However, there is a suggestion of a trend of decreasing 70 μm excess rates with later spectral types (Fig. 11). We note, however, that the mean age for the populations increases with later spectral types. It is possible that we are instead detecting a time-related effect, although the decay timescales identified by Rieke et al. (2005), Su et al. (2006), and Siegler et al. (2007) of hundreds of millions of years should

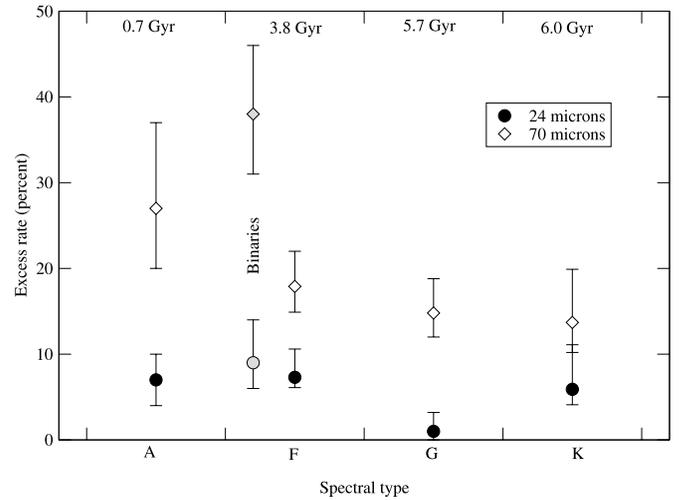


FIG. 11.—Excess rate as a function of spectral type for “old” stars, >600 Myr. The A stars values are from Su et al. (2006) and the binaries values are from Trilling et al. (2007) (a study of debris disks in A3–F8 binaries; different shading is used here to emphasize that the sample is defined differently, i.e., includes multiplicity as a requirement). The F, G, and K samples are the union of the data presented here and in Beichman et al. (2006b). The mean ages for each of the A, F, G, and K samples are given at the top of the figure (each value has a large standard deviation of perhaps 2–3 Gyr; additionally, ages are notoriously hard to derive for main sequence FGK stars). While formally these data are consistent with no dependence on spectral type, a decrease in excess as a function of spectral type is weakly suggested. However, this could easily be an age effect (see text and Fig. 12). The excess rate for (presumably old) M stars is 0%, with upper limits (binomial errors) of 2.9% at 24 μm and 12% at 70 μm (Gautier et al. 2007) (Table 4). [See the electronic edition of the *Journal* for a color version of this figure.]

long since have diminished all disks with ages of billions of years. We discuss this possibility in § 6.3.

Beichman et al. (2006b) remarked that the excess rates for K stars appeared to be lower than that for F and G stars, finding zero excesses among 23 stars later than K2 (and zero excesses among a larger combined sample of 61 K1–M6 stars). We include the Beichman et al. (2006b) data in our analysis here, and find that, formally, the excess rate for K stars is not significantly different than the excess rates for earlier (F and G) stars. As Beichman et al. (2006b) note, and we confirm, none of the six K stars with excesses in our larger sample are later than K2.

Part of the motivation for assembling the F stars program (PID 30211) was as a control sample for the binary star program presented in Trilling et al. (2007). In that study, 69 A3–F8 binary star systems were found, overall, to have relatively high excess rates: 9% at 24 μm and 40% at 70 μm . It is clear from our results here (see Fig. 11) that the (single) F stars excess rate is equal to or lower than the (single) A stars excess rate. The binaries excess rates remain significantly high compared to the control sample of single A and F stars.

Figure 8 shows that, in general, there is no trend of dust distance as a function of stellar effective temperature (spectral type). This may suggest that the processes that drive planetesimal formation do not depend strongly on a single critical temperature, as would be the case in the “ice line” model, where protoplanetary disk surface densities increase across certain temperature boundaries. However, our method for calculating dust distances may be too crude to see this effect. We note that all of the (minimum) dust distances given in Table 6 would fall within the planetary realm of our solar system (<30 AU). We are not observing disks that are far outside of the potential planetary realm of these systems.

We stated above that there is no particular trend for either fractional luminosity or dust distance with spectral type, but there is

an important caveat: no disks with large dust distances or relatively small fractional luminosities were identified among the latest stars in our sample. This dearth may simply allude to the fact that later stars are cooler. Dust at 25 AU around a K1 (5000 K) star would have a temperature around 50 K; this dust would have its peak emission near $70 \mu\text{m}$, and cooler (more distant) dust would have its peak emission longward. MIPS $70 \mu\text{m}$ observations of such a dust population, or a cooler one, would not readily show the presence of this excess. The lack of distant disks around K stars may therefore be an observational bias. Similarly, low fractional luminosity disks would be more difficult to detect around K stars than around earlier stars, so the lack of low fractional luminosity disks for later stars may also be due to observational bias. These observational biases may be corrected with sufficiently sensitive measurements at $\sim 100 \mu\text{m}$ (e.g., with *Herschel*).

To further address the question of whether there is any detectable trend of excess rate as a function of spectral type using existing published data, we compared the incidence of $70 \mu\text{m}$ excesses across these 5 spectral types (A, F, G, K, M), a total sample size of more than 350 stars. To avoid uncontrolled selection effects, we confined the comparison to stars that would have been detected at $70 \mu\text{m}$ at a level of at least 2 : 1 on the photosphere. We then applied a number of tests. First, we computed weighted average values of $R70$ (observed flux over predicted flux) as in Gautier et al. (2007). We find a value of ~ 5 for the A stars, but we discount this large average because of the small size of the sample (27 stars). The values for the F, G, K, and M stars are 1.16, 1.23, 1.06, and 1.025, respectively. Errors are difficult to estimate because the excesses are not normally distributed. We also computed straight averages of $R70$ for these same samples. Here, we calculate 4, 2.6, 1.8, 1.4, and 1.1 for the A, F, G, K, and M stars, respectively. Again, the values need to be interpreted with caution because error estimation is difficult. To circumvent the difficulties in determining errors, we binned the excesses into intervals of 0.5 in excess ratio and used the K-S test to determine if the resulting distributions were likely to have been drawn from the identical parent distribution. For each stellar type, we tested the relevant distribution against the distribution for all the stars, excluding the contribution of the spectral type in question. The result was a set of probabilities of 0.03, 0.8, 0.3, 0.3, and 0.01 that the types A, F, G, K, and M, respectively, were drawn from the same parent distribution as the other types. (For this test, a claim of a significant difference requires a probability of 0.05 or less that the samples are from the same distribution. Values of 0.3 imply that the G and K stars are 1σ different from their respective control samples.) From this suite of tests, we conclude that the incidence of excesses is different for old A stars and for M stars from that of the rest of our sample. We further deduce that there is a possibility of a difference appearing in the K stars from their lower average excess ratio. The distributions for F and G stars appear to be indistinguishable with our data. We employ this conclusion in the creation of an FG “supersample” (§ 6.4).

The higher excesses indicated for the old A stars could be an age effect, since the sample is by necessity significantly younger than the later types (which we selected in general to be > 1 Gyr in age). In fact, Gorlova et al. (2006) and Siegler et al. (2007) compare $24 \mu\text{m}$ excesses from young A and solar-like stars and find that the incidence is quite similar at a given age. Age effects would presumably cause an apparent decrease of excess incidence with later type among the F, G, and K stars because F stars will evolve off the main-sequence quickly enough to bias our sample toward younger objects (§ 6.3).

In the end, this discussion may still be suffering from a relatively small number of K stars sampled. An ongoing *Spitzer* program

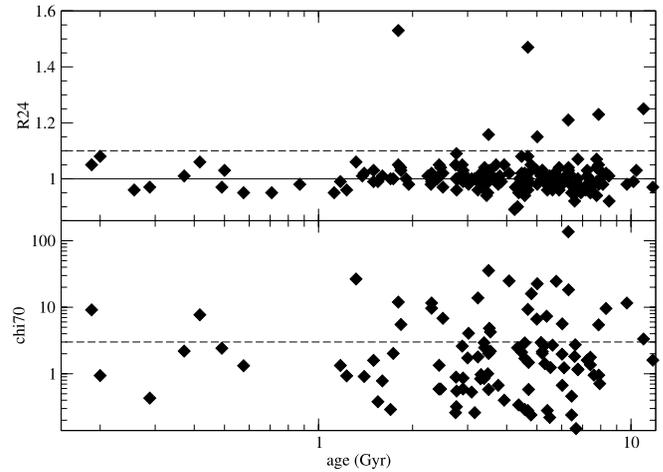


FIG. 12.—Individual $R24$ and χ_{70} determinations as a function of age for all stars in our FGK sample with good ages (164 have good ages and K -band photometry and therefore $R24$ measurements; 175 have good ages and χ_{70} measurements). No trend is apparent. The solid horizontal line in the top panel indicates $R24 = 1.0$, where there is no excess. (The no excess case in the bottom panel would be $\chi_{70} = 0.0$, which cannot be displayed on this logarithmic scale.) The horizontal dashed lines indicate our thresholds for excess ($R24 = 1.10$ and $\chi_{70} = 3.0$).

(PID 30490) to survey nearby stars that were not observed in other programs—a sample that includes ~ 400 K stars—should help unravel these statistics. Nonetheless, given our result, it is unlikely that future surveys will find a strong trend among F, G, and K stars of comparable ages—a range of spectral types that spans more than a factor of 50 in stellar luminosity. This behavior is counter to our expectations and is a challenge to models of debris disk evolution.

6.3. Effects of Age

The lack of strong dependence on spectral type lets us combine data on various types to study the evolution with stellar age. Figure 12 shows individual $R24$ and χ_{70} determinations for the stars in our FGK sample whose ages are known, as a function of system age. There is no correlation apparent for these individual sources, so we look to binned data in a larger combined sample for evidence of trends.

We once again take the union of the data presented here and that presented in Beichman et al. (2006b), but this time we include only spectral types F0–K5 from the Beichman et al. (2006b) sample (that is, we exclude the latest K stars). This is because the data we present in this paper covers the range F0–K5, and we want the best match to our combined sample. There are 10 stars in the F0–K5 TPF/SIM subsample that have no known ages, and 10 additional stars with ages less than 1 billion years. Of these 20, 2 systems have excesses (10%). Since this excess ratio is not significantly different from that of the overall FGK sample, and since the PID 30211 F stars sample is controlled for age but the PID 41 sample is not specifically controlled for age, we make no attempt to correct the larger sample for age.

Figure 13 shows excess rate as a function of age for this combined sample. To zeroth order, there is no trend as a function of age: a constant excess rate of $\sim 20\%$ adequately fits the data, being consistent at 1σ with the 10 Gyr data point and at 1.5σ with the 8 Gyr data point. Furthermore, the 10 Gyr bin has only seven targets in it, and the 8 Gyr bin has only 33 targets in it (still a relatively small number).

On the other hand, we note that the data shown in Figure 13 is suggestive of an excess rate that decreases with time through at least 8 Gyr. In this scenario, the 10 Gyr bin would be highly

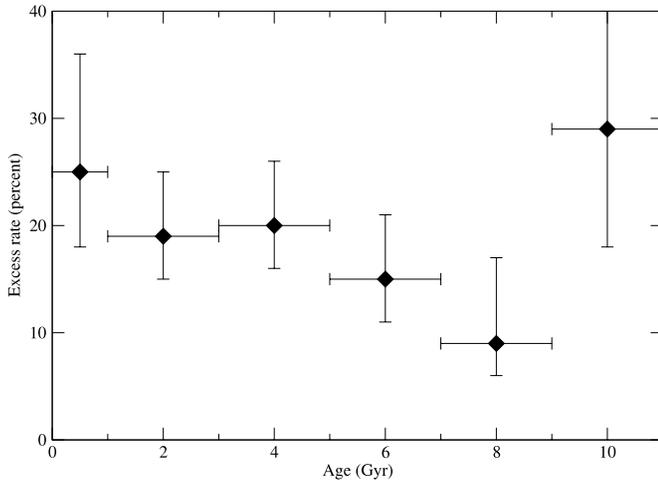


FIG. 13.—Excess rate as a function of age for the F0–K5 sample (our data plus that from Beichman et al. 2006b). The horizontal error bars show not the uncertainties in stellar age (which could be large) but rather the bin widths. The data could be consistent with essentially no trend as a function of age (that is, with one point low and another point low), but are suggestive of an overall decrease with age. This could indicate that debris disks continue to evolve even on billion-year timescales. However, this trend could also be a manifestation of the stellar components of these bins, since the older bins will be increasingly dominated by K stars (see Fig. 11). The number of stars in the six bins are as follows, from youngest to oldest: 24, 57, 60, 52, 33, and 7. Since the oldest bin has only seven stars in it (two with excesses), the high value may be a small number statistical anomaly.

anomalous, although we note that this bin is clearly affected by small number statistics (two excesses out of seven stars). In other words, there may be a real trend and a real evolution of planetary systems and debris disks even on the billion-year timescale. However, this may again be a manifestation of the (potential) observational bias shown in Figure 8, as follows.

The fraction of stars in a given age bin that are K stars increases for the later age bins. If K stars truly have fewer excesses (or fewer detectable excesses, according to observational biases) than other spectral types, Figures 13 and 14 might indeed be showing a real decrease with increasing age, caused not by a long-timescale evolution of planetary systems but by the increasing dominance of excess-deficient K stars at the oldest ages. The data present in our larger sample cannot distinguish between the competing possibilities of K stars preferentially lacking (detectable) disks, or of old stars increasingly lacking disks. It also remains to be seen whether the high excess rate for the oldest bin in Figure 13 is anything more than a small number statistics anomaly.

The overall high rate of excess incidence in our samples (17%) indicates that the 400 Myr decay timescale the drives the evolution of A star debris disks (Su et al. 2006) cannot drive the evolution of debris disks in our >1 Gyr Sun-like sample. Instead, Sun-like stars appear to have a relatively constant incidence of 15%–20% that is not strongly dependent on age, but may be weakly dependent on age through a very long timescale decrease.

6.4. Debris Disks around Sun-like Stars

Because there is no difference in excess rate between F and G stars, we can combine our sample of F0–G9 stars into a single population of “Sun-like” stars. To this sample of 169 stars we add the 56 F and G stars from Beichman et al. (2006b) to create an even larger sample of 225 Sun-like stars (213 stars at $24\ \mu\text{m}$). We refer to this merged sample of 213 and 225 stars as the “Sun-like supersample.” The excess rates for this supersample are

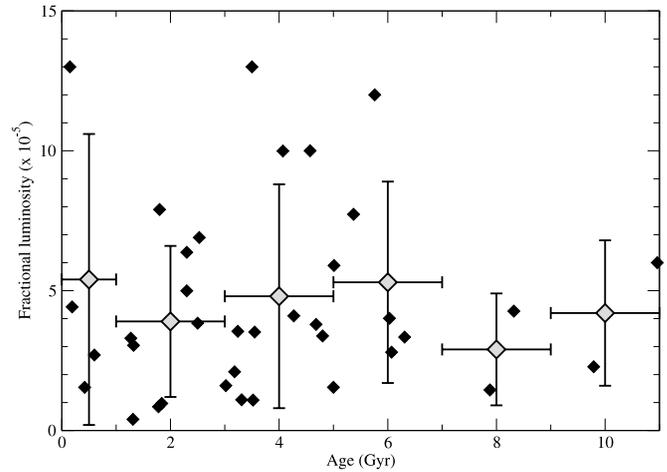


FIG. 14.—Fractional luminosity as a function of age for the excesses in the “all FGK” sample (our data plus that from Beichman et al. 2006b). The individual data points show fractional luminosity determinations from Tables 5 and 6 (using the maximum fractional luminosity values for the $70\ \mu\text{m}$ excess only cases). The larger gray symbols show the means in the same age bins as used in Fig. 13. The horizontal error bars show the bin widths, and the vertical error bars show the $1\ \sigma$ errors on the means. There is no obvious trend of fractional luminosity with age, although there is a lack of high fractional luminosity disks older than 6 Gyr. The systems with the three largest fractional luminosities have been omitted: ϵ Eri (0.3 Gyr, 29), HD 69830 (4.7 Gyr, 20), and HD 10647 (6.3 Gyr, 34) (where the fractional luminosities are given in units of 10^{-5}). Including these three obvious bright outliers does not change the result that no trend is evident, and just produces much larger error bars on the mean values. Our Sun has an age of 4.5 Gyr, and our solar system’s fractional luminosity is 10^{-6} – 10^{-7} .

$4.2^{+2.0}_{-1.1}\%$ at $24\ \mu\text{m}$ and $16.4^{+2.8}_{-2.9}\%$ at $70\ \mu\text{m}$ (Table 4). With this large supersample, we can now state the debris disk incidence rate for Sun-like stars with quite good confidence (small error bars).

6.5. Implications for Planetary System Formation

The majority of the debris disk systems that we present here have excesses at $70\ \mu\text{m}$ only, suggesting temperatures $\lesssim 100$ K and therefore an inner edge to the disks. These dusty debris disks are likely produced by collisions within a swarm of planetesimals akin to the asteroid belt or Kuiper Belt in our solar system. We interpret the cool temperatures we derive for the dust in these disks as evidence of inner disk holes where the surface density of dust is much smaller than in the planetesimal ring, and potentially zero. This architecture is strongly reminiscent of our solar system, where planets sculpt the edges of the planetesimal and dust belts. It may be that many of the systems we discuss here similarly have planets sculpting their dust distributions. In several cases, the known planets may indeed be the ones sculpting the inner edges of the disks (Tables 5 and 6). In addition, S. Lawler et al. (in preparation) have found, using IRS spectra, that the incidence of detectable levels of warm dust may be higher than the 4.2% we find here, indicating that dust in a region analogous to our solar system’s asteroid belt may also be somewhat common.

Bryden et al. (2007) show that the properties of disks around planet-bearing stars are unlikely to be similar to the properties of disks around stars without known planets. Briefly, the detection rates between these two populations are similar, but the planet-bearing stars are generally farther away and in more confused regions of the sky. They conclude that disks around planet-bearing stars are dustier (i.e., more massive), and probably more common, than disks around stars without known planets. In addition, Trilling et al. (2007) recently showed that the excess rate

for binary A–F stars is 9% and 40% at 24 and 70 μm , respectively, significantly higher than our results for FGK stars and for Sun-like stars. We see in Figure 11 that these excess rates are relatively high, compared to the large sample of single stars we present here. Combining these two studies, we find strong evidence that the presence of additional massive bodies (whether stellar or planetary companions) in stellar systems appears to promote higher excess rates. This effect may simply be dynamical—more massive bodies means more stirring, more collisions, and more dust—but it is not clear that such a process could remain effective for billions of years. Further work is necessary to explain these results.

Figure 11 shows that the transition from the high excess rate around A stars to the more modest excess rate around Sun-like stars is gradual. This gradual decay is likely an age effect (consider the mean ages of the samples given in Fig. 11). Our data show that excess rates for FGK stars decline slowly with stellar age, and it is not clear whether we are detecting a billion-year tail of debris disk evolution, a dependence on spectral type, and/or an observational bias.

Young (<1 Gyr) debris disks decay on 100–400 million year timescales (Rieke et al. 2005; Su et al. 2006; Gorlova et al. 2006; Siegler et al. 2007). The presence of excesses around 16% of Sun-like stars at billion year ages indicates that these old debris disks must be driven by a different evolutionary process than debris disks around those younger stars. One interpretation, using our solar system as an analogy, is that the younger systems are still active in a late heavy bombardment kind of dynamical upheaval. After a billion years, such large scale processes likely have ceased in all but the most unusual systems. Debris disks are then produced from collisions within remaining planetesimal belts (e.g., our asteroid belt) that have been dynamically excited by the previous eon's dynamical stirring. However, there is no trend of fractional luminosity with age (Fig. 14), although there is a lack of high fractional luminosity disks at old ages.

The presence of a debris disk indicates that planetary system formation progressed at least to the planetesimal stage in a given system. There is no apparent dependence on spectral type across Sun-like stars for fractional luminosity (i.e., dust mass), dust distance, or even excess rate. This indicates that the processes that give rise to a debris disk—planetesimal formation, dynamical stirring that produces collisions—must equally be insensitive to stellar parameters (temperature, mass, luminosity). This may argue that planetary system formation is quite robust—able to occur in many different conditions. While none of the debris disks

we observed are very similar to our own solar system, there can be no question that the process of planetary system formation is quite common.

7. SUMMARY

We observed nearly 200 FGK stars at 24 and 70 μm with the *Spitzer* Space Telescope to search for debris disks around nearby stars like the Sun. We identify excess emission, including a number of cases where the observed flux is more than 10 times brighter than the photospheric flux. We combine our data with results from several other sources to create a sample of more than 350 AFGKM stars. The incidence of debris disks in a large sample of Sun-like stars is $4.2^{+2.0}_{-1.1}\%$ at 24 μm (213 stars) and $16.4^{+2.8}_{-2.9}\%$ at 70 μm (225 stars). We find that the excess rates for A, F, G, and K stars are essentially indistinguishable, but with a suggestion of decreasing excess rate toward the later spectral types; this may be an age effect. The lack of strong trend among FGK stars of comparable ages is surprising, given the factor of 50 change in stellar luminosity across this spectral range. We also find that any decline in debris disk activity over the 1–10 Gyr time frame examined is very slow. This result contrasts with the more rapid decay found previously for stars 0.01–1 Gyr. This contrast suggests that the behavior at younger ages is dominated by events analogous to our solar system's late heavy bombardment. How debris disks are maintained for the ensuing billions of years remains an outstanding question.

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Facilities: Spitzer(MIPS)

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