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Evolution

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Deposited 06/13/2019

Citation of published version:

Spangler, C., et al. (2001): Dusty Debris around Solar-Type Stars: Temporal Disk
Evolution. *The Astronomical Journal*, 555(2). DOI: <https://doi.org/10.1086/321490>

DUSTY DEBRIS AROUND SOLAR-TYPE STARS: TEMPORAL DISK EVOLUTION

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Received 2001 January 10; accepted 2001 March 8

ABSTRACT

Using *ISO-ISOPHOT*, we carried out a survey of almost 150 stars to search for evidence of emission from dust orbiting young main-sequence stars, both in clusters and isolated systems. Over half of the detections are new examples of dusty stellar systems and demonstrate that such dust can be detected around numerous stars older than a few times 10^6 yr. Fluxes at 60 and either 90 or 100 μm for the new excess sources together with improved fluxes for a number of *IRAS*-identified sources are presented. Analysis of the excess luminosity relative to the stellar photosphere shows a systematic decline of this excess with stellar age consistent with a power-law index of -2 .

Subject headings: circumstellar matter — infrared: stars — open clusters and associations: general — planetary systems

1. INTRODUCTION

Circumstellar disks are generally accepted as a natural by-product of star formation (e.g., Shu et al. 1993), and there is considerable observational evidence for the presence of such disks around very young solar mass stars (e.g., Sargent 1996 and references therein; Natta, Grinin, & Mannings 2000; Andre, Ward-Thompson, & Barsony, 2000; Mundy, Looney, & Welch 2000; Wilner & Lay 2000). The *IRAS* detection of far-IR radiation from main-sequence stars at a level much greater than could be attributed to the stellar photospheres was, nonetheless, unexpected (e.g., Aumann et al. 1984). These stars became known as “Vega-type” stars, after one of the first examples. This IR excess radiation was interpreted as thermal emission from dust in orbit about the stars (see Backman & Paresce 1993 and references therein; Lagrange, Backman, & Artymowicz 2000). Early coronagraphic observations of scattered light from the Vega-type star β Pictoris indicated an edge-on disk morphology (Smith & Terrile 1984). Recent imaging of thermal emission at mid-IR and millimeter wavelengths from Vega-type stars, including HR 4796A, MWC 480, and ϵ Eridani, continues to provide support for the disk interpretation (Koerner et al. 1998; Jayawardhana et al. 1998; Holland et al. 1998; Mannings, Koerner, & Sargent 1997; Greaves et al. 1998). Dramatic disklike images in reflection around HR 4976A and the Herbig Ae/Be star HD 141569 have recently been published (Schneider et al. 1999; Weinberger et al. 1999; Augereau et al. 1999).

Typically, the ages of T Tauri stars with associated disks are of order 10^6 yr old or less. The Vega-type stars have ages ranging from 10^7 to 10^9 yr. While known examples of Vega-type systems are fairly well studied, their limited number provides little information on the evolution of circumstellar dust during these later epochs, yet it is these later epochs that are of critical importance to understanding the

development of planetary systems (Lagrange et al. 2000). Gathering a statistical sample of intermediate-age objects is difficult. Not only is the time to evolve from protoplanetary to planetary debris disks likely to be brief, but disk emission drops dramatically with age as grains grow and/or dissipate, reducing the emitting surface area. As planetary embryos form close to the stars, the hot inner dust is probably cleared. There are also many mechanisms capable of reorganizing or removing the outer primordial circumstellar dust, including grain growth, Poynting-Robertson drag, and radiation pressure, in times short compared to the ages of older Vega-type stars. In fact, for older stars to exhibit dusty disks there must be an ongoing source of particles; a favored explanation is that some planetesimals are colliding and fragmenting. There is substantial evidence that extrasolar planets are common (Marcy, Cochran, & Mayor 2000), implying that smaller planetesimals, collisions of which could provide a reservoir of circumstellar dust, are also common.

Since thermal emission from the little remaining outer, cooler material peaks at wavelengths of 50–150 μm , airborne or space-based instruments are required to detect intermediate-age and older disks. However, *IRAS*, with sensitivities of a few hundred mJy at 60 and 100 μm , detected only the nearest and brightest disks, mostly those associated with main-sequence stars of spectral type A. In addition, the low spatial resolution of *IRAS* limited the ability to determine if emission was associated with a specific object, particularly at 100 μm where galactic cirrus confusion is significant. The *Infrared Space Observatory (ISO)*, with a factor of 2 improvement in resolution, $46''$ pixels at 60–100 μm , and an order of magnitude increase in sensitivity over *IRAS*, has expanded our capability to search for circumstellar dust.

Here we describe our *ISO* program³ of observations to search for dusty circumstellar material, especially around stars of spectral types F and G, and also to study the evolu-

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³ A NASA/*ISO* Key Project.

tion of disks from the pre-main-sequence (PMS) through the main-sequence stages. Details of the target selection are presented in § 2; an account of observations, data reduction, and basic results is given in § 3; and excess radiation calculations are described in § 4. Results and implications of our observations are discussed in § 5 and summarized in § 6.

2. TARGET SELECTION

Our targets fell into three distinct categories:

1. Main-sequence members of relatively nearby (generally less than 120 pc) open clusters including α Persei, Coma Berenices, Hyades, Pleiades, and the Ursa Major nucleus and stream. Cluster ages are between 50 and 700 Myr, and the target stars span spectral types A–K.
2. Selected classical and weak-line T Tauri stars in the Chamaeleon I, Scorpius, and Taurus star-forming clouds at ~ 150 pc. Some of these were detected by *IRAS*, but beyond $60 \mu\text{m}$ only upper limits to the fluxes are available.
3. A small sample of relatively nearby (less than 60 pc) isolated stars with indications of youth.

A major problem in defining an evolutionary sequence for circumstellar disk characteristics arises because it is difficult to assign an age to an isolated star. Age determinations rely on a number of factors including the star's position in the H-R diagram, its metallicity, and the depth of its convection layer. Even with well-defined observable parameters, the calculated age can vary greatly depending on stellar models used. For stars in clusters, a more accurate age determination is possible based on the main-sequence turnoff point. By selecting target objects from well-studied clusters, ages are fairly well defined. In order to encompass a variety of evolutionary characteristics in any associated disk, stars in our sample clusters range from the PMS, ages $\lesssim 10$ Myr, to the young main sequence, ages up to 1 Gyr. Reasons to include PMS stars in our study are to establish the initial characteristics of the dusty material whose evolution we wish to understand and to enable an assessment of the fraction of weak-line T Tauri stars (WTTs) that support

disks. WTTs are similar to classical T Tauri stars (CTTs) but exhibit only weak H α emission and show no other indications of the presence of an accreting disk (Calvet, Hartman, & Strom 2000).

Since the contrast between radiation from the stellar photosphere and the disk increases with longer wavelengths, we confined our search to *ISO*'s 60 and 90/100 μm wavelength bands. *IRAS* 3 σ sensitivity limits at 60 and 100 μm were typically 200–300 mJy and 500–3000 mJy, respectively, depending on the degree of cirrus confusion. Pre-launch sensitivity estimates for ISOPHOT, on which we based our original target selections, were of order 1 mJy (3 σ rms) with a 256 s observation in these bands. Since an F0 V star at 100 pc typically has photospheric fluxes of 3.6 and 1.2 mJy at 60 and 100 μm , respectively, we expected that photospheric fluxes characteristic of near-solar-type stars could be detected out to distances of about 100 pc. Beyond this distance and for later type stars, only fairly strong emission in excess of photospheric values would be detected. Consequently, our candidate open clusters needed to be nearby, $\lesssim 100$ pc. In the late stages of star formation, at ages $\lesssim 50$ Myr, disks are more likely to be brighter and could be detected up to about 200 pc. Our choice of candidate clusters was also constrained by conflicts with *ISO* core programs and the *ISO* pointing restrictions. Complete surveys were out of the question. Nevertheless, the *ISO* lifetime was sufficient to enable some observations in all clusters we considered interesting.

Table 1 lists the clusters from which we selected targets, along with their ages, distances, the number of targets observed, observing modes, and integration times.

Target stars in the young open clusters were selected from lists of cluster members published by Prosser (1992) for α Persei; by Boesgaard (1987) and Bounatiro (1993) for Coma Berenices; by Schwan (1991) for the Hyades; by Soderblom et al. (1993a) for the Pleiades; and by Boesgaard, Budge, & Burck (1988), Soderblom & Clements (1987), and Soderblom et al. (1993b) for Ursa Major. Within each cluster, preference was given to targets with relatively low cirrus confusion, as determined from the *IRAS* Sky Survey back-

TABLE 1
PROPERTIES OF OBSERVED CLUSTERS

Cluster Name	Age (Myr)	Reference	Distance (pc)	Reference	Number of Targets	Observation Mode	Integration Time (s)
Upper Scorpius	1–10	1	145	1	2	Raster	53/raster pt., 473 total
Chamaeleon Ia	1–20	2	140	3	18	Chopped	128 on-target, 128 off-target
Chamaeleon Ib	3–40	4	150	4	11	Raster	40/raster pt., 346 total
					2	Raster	53/raster pt., 473 total
Taurus	10–40	5	140	6	8	Raster	53/raster pt., 473 total
α Persei	50	7	185	8	6	Raster	40/raster pt., 346 total
					13	Raster	53/raster pt., 473 total
Pleiades	120	7	118	8	14	Raster	53/raster pt., 473 total
Ursa Major	300	9	10–40	10	13	Chopped	128 on-target, 128 off-target
					6	Raster	53/raster pt., 473 total
Coma Berenices	500	11	88	11	18	Chopped	128 on-target, 128 off-target
					8	Staring	128 on-target, 128 off-target
Hyades	625	12	46	12	9	Raster	53/raster pt., 473 total
Young field stars	60–630	13	25–125	10	6	Chopped	128 on-target, 128 off-target, 60 μm
							64 on-target, 64 off-target, 100 μm
					13	Raster	46/raster pt., 410 total

REFERENCES.—(1) Preibisch & Zinnecker 1999. (2) Lawson et al. 1996. (3) Feigelson et al. 1993. (4) Alcalá et al. 1997. (5) Bouvier et al. 1997. (6) Kenyon, Dobrzycka, & Hartmann 1994. (7) Meynet, Mermilliod, & Maeder 1993. (8) Robichon et al. 1999. (9) Eggen 1973. (10) *Hipparcos*. (11) Odenkirchen, Soubiran, & Colin 1998. (12) Perryman et al. 1998. (13) See Table 2.

ground measurements. In Coma Berenices, a sparse cluster with few confirmed members and relatively low cirrus, we included nearly all dwarf stars with spectral types later than A0. By including all possible Ursa Major candidates not reserved by *ISO* core programs, we sampled a wide range of spectral types in this cluster, from early A to early K, although most objects are of spectral types F and G. For the remaining clusters where there were larger numbers of candidates available, we gave preference to stars with spectral types near solar, mostly late F- and G-type stars. When choosing targets in the Hyades, we also took into account indications of potential far-IR excesses based on *IRAS* 12 and 25 μm data. Binarity was not a cause for exclusion from our sample because we hoped to increase understanding of the relationship between circumstellar dust and multiplicity. Finally, we made efforts to include targets with a range of rotational velocities to assess the relationship between the presence of a disk and stellar rotation.

Very young stars included CTTs and WTTs in the Chamaeleon I association selected from the published lists of Gauvin & Strom (1992) and Alcalá et al. (1995), WTTs in Taurus from Wichmann et al. (1996), and WTTs in the Upper Scorpius association from Walter et al. (1994). In Chamaeleon I, most sources have measured *IRAS* fluxes at 12 and/or 25 μm but lack good quality measurements at 60 and/or 100 μm . Other WTTs were selected to span the range of the limited age estimates available and for lower cirrus confusion.

We also included 19 field stars (hereafter referred to as young field stars) that exhibited indications of youth, primarily based on published chromospheric activity age indicators. We intended to limit distances to less than 60 pc, but following the publication of *Hipparcos* data, it became clear that two observed stars are actually more distant than this cutoff. Like the cluster stars, the young field stars span the age range 60–800 Myr with a median of 180 Myr. They encompass spectral types A–K but are concentrated on spectral types F and G. Individual stellar ages are presented in Table 2.

3. OBSERVATIONS AND RESULTS

We selected the ISOPHOT C100 detector (Lemke et al. 1996) for our target observations. Targets were observed throughout the *ISO* mission, and our observing strategies changed as our understanding of ISOPHOT performance

improved. The first group of 63 observations was made between 1996 June and 1996 December. The majority employed the 60 and 100 μm filters and the triangular chopping mode with a 150" throw. Eight stars in Coma Berenices (see Table 3) were observed with a "staring chain," an on-target observation followed by a background observation 3' north of the target, then the next on-target observation, etc., first in the 60 μm filter, then in the 100 μm filter. The second group of 85 observations was made between 1997 June and 1998 March using the 60 and 90 μm filters and the raster mode in a 3×3 grid with 46" steps. A list of total integration times and number of targets observed in each cluster is presented in Table 1.

Data reduction made use of the ISOPHOT Interactive Analysis (PIA) package, Version 7.3 (Gabriel et al. 1997) and was supported by our own routines. Our final results are based on data from Off-Line Processing (OLP), Version 7.0. Standard reduction parameters were used for linearization of ramps, two-threshold deglitching, first-order polynomial voltage ramp fitting, and reset interval correction. Slope deglitching was slightly modified by using a sigma range of 2.4 and max/min clipping. Chopped observations were corrected with the default chopper loss factors given by the ISOPHOT Team (Gabriel et al. 1997). Dark current subtraction employed the orbital-dependent model values. Finally, to limit the influence of the nonlinear response of the detector to a change in flux, we discarded the first third of each raster pointing.

We calibrated the data with the onboard Faint Calibration Source (FCS) measurements. Since there is significant evidence for detector drifts during observation, the best strategy obtains calibration measurements immediately before and after a target observation. For the staring and chopped observations, which were all made before the detector drift was well understood, FCS measurements were made at the beginning and end of a group of individual observations. Calibration factors were then interpolated for each target and background observation. For raster observations, FCS measurements were made immediately before and after each target observation and calibration factors interpolated at each raster step. The application of the FCS calibration also removes a first-order flat field. Residual effects exist, but in general their magnitude is less than the other observational uncertainties. As far as possible, these FCS-based calibrations were cross-checked by comparing

TABLE 2
YOUNG FIELD STAR AGES

Object	Age (Myr)	Reference	Object	Age (Myr)	Reference
HD 105.....	500	1	HD 160934.....	...	...
HD 1405.....	60	2	HD 171488.....	80	6
HD 16884.....	800	3	HD 175897.....	100	1
HD 35850.....	230	4	HD 177996.....	300	1
HD 36705.....			HD 180445.....	160	1
HD 37484.....	80	3	HD 197890.....	300	7
HD 54579.....	160	1	HD 202917.....	180	1
HD 119022.....	160	1	HD 209253.....	400	4
HD 129333.....	300	5	HD 220140.....	60	8
HD 134319.....	500	5	...	...	...

REFERENCES.—(1) Henry et al. 1996. (2) Griffin 1992. (3) Favata et al. 1993. (4) This paper. (5) Duncan et al. 1991. (6) Henry, Fekel, & Hall 1995. (7) Jeffries 1995. (8) Mantegazza et al. 1992.

TABLE 3
 TARGETS OBSERVED IN CHOPPED MODE WITH FLUXES AND UNCERTAINTIES

Target Name	Spectral Type	60 μm (Jy)	rms (Jy)	100 μm (Jy)	rms (Jy)	Target Name	Spectral Type	60 μm (Jy)	rms (Jy)	100 μm (Jy)	rms (Jy)
Chamaeleon I											
Sz 4	CTTS	0.219	0.038	0.210	0.060	Glass Ia	WTTS	12.970	0.236	7.216	0.445
SZ Cha	CTTS	3.545	0.177	2.546	0.400	HM 19	CTTS	-0.193	2.360	-0.572	3.176
TW Cha	CTTS	0.528	0.078	0.267	0.074	VX Cha	WTTS	0.030	0.063	-0.155	0.193
HM 5	WTTS	0.020	0.055	0.080	0.156	WX Cha	CTTS	0.232	0.045	0.192	0.134
CED 110	WTTS	7.943	0.128	17.995	8.806	GK-1	CTTS	0.566	2.244	2.001	5.104
UX Cha	WTTS	0.024	0.023	0.083	0.091	WY Cha	CTTS	0.303	0.165	0.832	0.548
UZ Cha	WTTS	0.268	0.081	0.229	0.093	CHX 18	WTTS	0.530	0.085	0.372	0.118
Lk Ha 332-17	CTTS	6.715	1.460	8.338	5.474	HM 32	CTTS	0.462	0.029	0.353	0.077
Sz 23	WTTS	0.575	3.033	0.183	6.940	HM Anon	WTTS	0.831	0.104	0.793	0.269
Ursa Major											
HD 109011	K2 V	0.019	0.095	-0.037	0.064	HD 124674	F1 V	0.050	0.069	-0.101	0.100
HD 109647	K0	0.052	0.066	0.089	0.032	HD 125451	F5 IV	0.171	0.018	0.004	0.045
HD 110463	K3 V	0.059	0.111	-0.047	0.024	HD 139798	F2 V	0.067	0.022	0.007	0.049
HD 111456	F5 V	0.069	0.040	0.038	0.070	HD 141003	K3 V	0.502	0.326	0.208	0.212
HD 113139	F2 V	0.025	0.044	0.016	0.037	HD 147584	G0 V	0.099	0.072	0.128	0.103
HD 115043	G2 V	0.054	0.023	0.024	0.025	HD 180777	A9 V	0.014	0.053	0.061	0.080
HD 116656	A2 V	0.171	0.022	0.016	0.022	...	...	...	...	...	...
Coma Berenices											
HD 105805	A3 V	0.034	0.045	0.011	0.019	HD 107793 ^a	F8 V	0.011	0.018	-0.007	0.008
HD 106103	F5 V	0.005	0.041	0.003	0.008	HD 107887 ^a	F5 V	-0.009	0.033	0.010	0.046
HD 106691	F3 V	0.091	0.091	0.022	0.029	SAO 82286 ^a	G1 V	0.027	0.023	0.008	0.014
HD 106946	F2 V	0.061	0.052	-0.040	0.027	HD 107935 ^a	A7 V	0.085	0.063	0.050	0.052
HD 107067	F9 V	0.170	0.072	0.019	0.061	BD +26°2342	K0 V	0.004	0.031	0.001	0.032
HD 107132	F7 V	0.031	0.042	-0.001	0.027	HD 108102	F8 V	0.150	0.036	0.031	0.033
HD 107131	A7 V	0.044	0.023	0.006	0.018	HD 108154	F8 V	0.051	0.038	-0.014	0.015
HD 107214	G0 V	0.105	0.055	-0.030	0.026	HD 108226 ^a	F6 V	0.086	0.048	-0.007	0.056
HD 107399	G0 V	0.023	0.049	0.023	0.015	Tr 132 ^b	G5 V	-0.048	0.035	0.063	0.034
HD 107583 ^a	G1 V	0.061	0.078	0.000	0.018	HD 108651	A0	0.177	0.055	0.022	0.041
HD 107611 ^a	F6 V	-0.009	0.031	0.013	0.039	SAO 82335	G9 V	-0.089	0.048	0.005	0.022
HD 107685	F5 V	0.100	0.045	0.006	0.012	HD 108967	F6 V	0.051	0.038	0.042	0.019
HD 107700 ^a	A2 V + G7 III	0.067	0.014	0.025	0.029	HD 109307	A4 V	0.027	0.034	0.009	0.044
Young Field Stars											
HD 16884	K5 V	0.137	0.070	0.002	0.046	HD 129333	F8	0.018	0.026	-0.020	0.043
HD 36705	K1 IIIp	0.008	0.045	0.051	0.029	HD 160934	K7	-0.014	0.025	-0.004	0.031
HD 119022	G2 IV/V	0.047	0.056	0.125	0.091	HD 175897	G0 V	0.043	0.054	-0.041	0.031

NOTE.—Spectral type information from SIMBAD.

^a Staring chain observation.

^b Replace “Tr” with “Cl Melotte 111” to find in SIMBAD.

the method of calibration from the observed *ISO* and published *IRAS* backgrounds and a number of actual *IRAS* source measurements as described by Silverstone, Becklin, & Spangler (1997), Silverstone (2000), and Spangler et al. (1999) and were found to be consistent. A more detailed discussion of the calibration comparisons is given in the Appendix. We are confident that the PIA calibration using the FCS measurements is sufficiently reliable to support our conclusions. Corrections for the point-spread function (PSF) were applied using model calculations that give the fraction flux falling on the center pixel of the array as 0.66, 0.57, and 0.54 at 60, 90, and 100 μm , respectively (Laureijs 1999).⁴ A more detailed discussion of the standard data reduction procedures is presented by Silverstone (2000).

For all observing strategies used here, a source was considered detected if the flux at the on-target (center) pixel exceeded 3 times the standard deviation of the flux on the 8 surrounding pixels. This provided a conservative approach to problematic observations. In all cases, the standard deviation of the flux on the surrounding pixels is higher than any other statistical uncertainties associated with the observation. In five cases, all in the Chamaeleon and Scorpius clusters, the source was extended to 1 outer pixel. This pixel was excluded from the calculation of the background standard deviation. At both 60 and 100 μm , typical 3 σ noise limits for chopped observations were 100 mJy in 256 s. For raster observations, corresponding limits were 50 mJy at 60 μm and 40 mJy at 90 μm in 473 s. In regions of very low cirrus, the noise limits were as much as a factor of 3 lower. Conversely, in regions with high cirrus confusion, the noise limits were as much as a factor of 5 higher. These sensi-

⁴ Article available at http://www.iso.vilspa.esa.es/users/exp_lib/PHT_list.html.

TABLE 4
TARGETS OBSERVED IN RASTER MODE WITH FLUXES AND UNCERTAINTIES

Target Name	Spectral Type	60 μ m (Jy)	rms (Jy)	90 μ m (Jy)	rms (Jy)	Target Name	Spectral Type	60 μ m (Jy)	rms (Jy)	90 μ m (Jy)	rms (Jy)
Upper Scorpius											
ScoPMS 60	WTTS	0.003	0.008	0.002	0.011	ScoPMS 214	WTTS	0.116	0.008	0.129	0.034
Chamaeleon I											
RX J0850.1–7554	WTTS	–0.002	0.021	0.020	0.006	RX J1035.8–7859	WTTS	0.013	0.036	0.003	0.011
RX J0853.1–8244	WTTS	0.026	0.019	0.000	0.007	RX J1048.9–7765	WTTS	–0.029	0.030	0.007	0.011
RX J0917.2–7744	WTTS	0.005	0.019	0.008	0.012	RX J1125.8–8456	WTTS	0.019	0.011	–0.001	0.005
RX J0928.5–7815	WTTS	0.003	0.034	0.002	0.012	RX J1203.7–8129	WTTS	–0.006	0.019	–0.002	0.008
RX J0952.7–7933	WTTS	0.005	0.022	0.003	0.009	RX J1225.3–7857	WTTS	0.004	0.009	–0.003	0.009
RX J1007.7–8504	WTTS	0.001	0.019	–0.007	0.007	RX J1325.7–7955	WTTS	–0.017	0.014	0.010	0.014
RX J1009.6–8105	WTTS	0.002	0.018	–0.004	0.009	...	...	...	...	...	...
Taurus											
RX J0408.2+1956	WTTS	0.000	0.009	0.009	0.009	RX J0420.4+3123	WTTS	0.012	0.040	0.006	0.016
RX J0409.2+2901	WTTS	0.011	0.032	–0.005	0.021	RX J0423.7+1537	WTTS	0.029	0.026	0.006	0.018
RX J0412.8+2442	WTTS	–0.010	0.013	0.011	0.015	RX J0431.3+2150	WTTS	–0.013	0.021	–0.003	0.015
RX J0415.3+2044	WTTS	0.010	0.014	–0.010	0.019	RX J0457.0+1517	WTTS	–0.002	0.015	0.016	0.009
α Persei ^a											
HE 061	F0	–0.005	0.017	–0.003	0.015	HE 660	F4 V	–0.007	0.018	–0.018	0.017
HE 143	F8 IV–V	0.025	0.017	0.006	0.012	HE 715	F5 V	0.003	0.013	0.007	0.011
HE 299	F6 V	0.014	0.016	0.011	0.014	HE 733	F6 V	0.009	0.019	0.012	0.018
HE 361	F4 V	0.036	0.010	0.017	0.033	HE 750	F9 V	–0.009	0.020	–0.005	0.014
HE 387	F2 V	0.005	0.009	0.009	0.006	AP 166	G0	0.003	0.012	–0.004	0.014
HE 421	F2 V	0.015	0.008	0.005	0.007	HE 794	F6 V	–0.007	0.025	0.002	0.012
HE 490	F4 V	–0.012	0.012	–0.017	0.015	HE 1101	G4	–0.006	0.021	–0.006	0.015
AP 14	G4	0.001	0.017	0.013	0.013	HE 1160	F7	0.015	0.018	0.004	0.017
HE 621	F4 V	–0.002	0.016	0.019	0.017	HE 1181	G2	–0.012	0.017	0.005	0.009
HE 635	A9 V	0.004	0.012	0.005	0.011	...	...	...	...	...	...
Pleiades ^b											
HII 1132	F5 V	0.028	0.010	0.026	0.010	HII 2341	G4 V	0.006	0.027	–0.003	0.009
HII 1182	G5 V	–0.011	0.011	–0.006	0.005	HII 2462	G4 V	0.008	0.023	0.002	0.021
HII 1220	G8 V	0.013	0.018	–0.007	0.014	HII 2506	F8 V	0.002	0.018	0.006	0.010
HII 1593	G6 V	0.015	0.015	0.001	0.015	HII 2786	G0	0.006	0.018	–0.010	0.018
HII 1924	G0 V	–0.011	0.019	0.000	0.015	HII 3163	K2	0.009	0.023	0.038	0.011
HII 2284	G0 V	–0.013	0.016	0.003	0.022	HII 3179	G0 V	0.019	0.031	0.012	0.005
HII 2311	G0 V	–0.013	0.021	–0.006	0.024	HII 3197	K3 V	–0.024	0.023	0.010	0.013
Ursa Major											
HD 11131	G0 V	0.005	0.004	0.006	0.005	HD 72905	G1 V	0.077	0.014	0.053	0.012
HD 13594	F5 V	0.000	0.004	0.009	0.009	HD 165185	G5 V	0.004	0.004	0.005	0.011
HD 13959	K4 V	0.011	0.007	–0.002	0.007	HD 184960	F7 V	0.050	0.016	0.046	0.012
Hyades											
HD 27429	F3 V	0.001	0.017	–0.007	0.024	HD 28344	G2 V	0.016	0.026	0.007	0.018
HD 27459	F0 V	0.050	0.013	–0.004	0.012	HD 28677	F4 V	–0.001	0.018	0.002	0.016
HD 27561	F5 V	0.007	0.016	0.017	0.022	HD 28992	G1 V	–0.006	0.018	0.008	0.022
HD 27848	F6 V	0.018	0.025	0.012	0.016	HD 29225	F5 V	0.009	0.022	–0.009	0.016
HD 28205	F8 V	–0.012	0.015	–0.003	0.005	...	...	...	...	...	...
Other											
HD 151044	F8 V	0.088	0.016	0.103	0.022	...	...	...	...	...	...
Young Field Stars											
HD 105	G0 V	0.143	0.026	0.167	0.008	HD 177996	K1 V	0.019	0.024	0.042	0.017
HD 1405	G5	–0.025	0.016	–0.009	0.009	HD 180445	G8 V	0.032	0.018	0.008	0.012
HD 35850	F7 V	0.049	0.014	0.050	0.012	HD 197890	K0 V	0.002	0.021	0.006	0.009
HD 37484	F3 V	0.115	0.022	0.084	0.011	HD 202917	G5 V	0.050	0.020	0.038	0.015
HD 54579	G0 V	0.000	0.024	–0.003	0.020	HD 209253	F6/F7 V	0.127	0.021	0.107	0.015
HD 134139	G5	0.048	0.019	0.012	0.011	HD 220140	G9 V	–0.001	0.011	–0.006	0.013
HD 171488	G0 V	0.032	0.024	0.017	0.018	...	...	...	...	...	...

NOTE.—Spectral type information from SIMBAD.

^a HE: Heckmann, Dieckvoss, & Kox 1956; AP: Stauffer, Hartmann, & Burnham 1985; to find in SIMBAD, replace “HE” with “Cl Melotte 20” and prepend “Cl* Melotte 20” to AP.

^b Names from Hertzprung 1947; to find in SIMBAD, replace “HII” with “Cl Melotte 22.”

TABLE 5
PROPERTIES OF STARS WITH INFRARED EXCESS

Target	SpT	m_v	$B-V$	$v \sin i$ (km s ⁻¹)	Distance (pc)	Age (Myr)	Multiplicity
Upper Scorpius							
ScoPMS 214.....	K0 IV	11.2	1.24	90	160	2	...
Chamaeleon I: Detections							
Sz 4.....	CTTS	...	...	...	140	...	...
SZ Cha.....	CTTS	11.7	1.58	...	140	8	Trinary; sep. ~13" and ~5"
TW Cha.....	CTTS	13.3	2.02	...	140	20	...
CED 110.....	WTTS	11.3	1.41	75	140	5	...
UZ Cha.....	WTTS	14.9	1.72	...	140	...	...
Lk H α 332-17.....	CTTS	10.7	1.20	30	140	4	Binary; sep. <5"
Glass Ia.....	WTTS	12.8	1.47	...	140	3	Glass Ib; sep. ~2"
WX Cha.....	CTTS	14.8	1.69	...	140	5	Binary; sep. <1"
WY Cha.....	CTTS	14.0	1.57	...	140	4	...
XX Cha.....	WTTS	15.3	1.53	...	140	40	...
CHX 18N.....	WTTS	12.1	1.31	25	140	8	...
HM Anon.....	WTTS	11.1	1.15	<16	140	10	Binary; sep. <1"
HM 32.....	CTTS	13.5	1.44	...	140	5	...
RX J0850.1-7554.....	WTTS	10.6	0.74	45	170?	16	...
Chamaeleon I: Nondetected or Contaminated Stars							
HM 5.....	WTTS	...	...	...	140	...	...
UX Cha.....	WTTS	...	...	...	140	...	...
Sz 23.....	WTTS	...	...	...	140	...	One of at least three companions to VW Cha; sep. ~17"
HM 19.....	CTTS	...	...	...	140	...	...
VX Cha.....	WTTS	...	...	...	140	...	...
GK-1.....	CTTS	...	...	...	140	...	...
α Persei							
HE 361.....	F4 V	9.7	0.43	30	184.2	65	...
Pleiades							
HII 1132.....	F5 V	9.4	0.45	40	120	120	...
HII 3163.....	K2	12.7	0.96	60	120	120	...
Ursa Major							
HD 72905.....	G1 V	5.6	0.62	10	14.3	300	...
HD 125451.....	F5 IV	5.4	0.39	40	26.1	300	Binary; sep. ~160"
HD 139798.....	F2 V	5.8	0.35	...	35.7	300	...
HD 184960.....	F7 V	5.7	0.48	7	25.6	300	...
Coma Berenices							
HD 107067.....	F8	8.7	0.52	6	68.8?	500	SB?
HD 108102.....	F8	8.2	0.49	35	107.1	500	SB2
HD 108651.....	A0	6.7	0.22	18	79.0	500	SB2
Hyades							
HD 27459.....	F0 V	5.3	0.23	68	47.2	625	...
Young Field Stars							
HD 105.....	G0 V	7.5	0.60	13	40.2	500	...
HD 35850.....	F7 V:	6.3	0.50	40	26.8	230	...
HD 37484.....	F3 V	7.2	0.37	42	59.5	80	...
HD 134319.....	G5	8.4	0.64	...	44.3	500	...
HD 177996.....	K1 V	7.9	0.86	4	31.8	300	SB*
HD 202917.....	G5 V	8.7	0.65	12	45.9	180	...
HD 209253.....	F6/F7 V	6.6	0.46	16	30.1	400	...
Other							
HD 151044.....	F8 V	6.5	0.54	5	29.4	>300	...

NOTE.—The list also contains the Chamaeleon I targets observed but not clearly detected for comparison.

* From Soderblom, King, & Henry 1998.

TABLE 6
PMS STARS WITH INFRARED EXCESS IN CHAMAELEON I AND UPPER SCORPIUS

TARGET	IRAS FLUXES				ISO FLUXES ^a		f_d ($\times 10^{-4}$)	NOTES
	12 μm (mJy)	25 μm (mJy)	60 μm (mJy)	100 μm (mJy)	60 μm (mJy)	100 μm (mJy)		
Sz 4	88	142	241	<4300	219	210	240	
SZ Cha	260	1390	3680	3410	3545	2546	910	1
TW Cha	238	405	450	110 ^b	528	267	480	
CED 110	336	140	<4930	17130	7945	<17995	250	2
UZ Cha	112	128	<210	<4650	268	229	320	
Lk H α 332-17	2200	3370	6450 ^b	8550 ^b	6715	<8338	640	3
Glass Ia	10400	14720	9570	<10400	12970	7216	4120	
WX Cha	500	514	250 ^b	<15000	232	≤ 200	2240	
WY Cha	<500	477	830 ^b	20610 ^b	≤ 300	≤ 830	720	4
XX Cha	395	560	590	<3360	≤ 530	≤ 360	550	5
CHX 18N	≤ 200	≤ 300	...	5
HM Anon	<250	<250	790	4640	831	793	130	6
HM 32	93	212	660	1080 ^b	462	353	1010	7
RX J0850.1–7554	<150	<200	<100	<200	<62	20 ^c	6.9	8
ScoPMS 214	<400	<450	<600	<3000	116	129 ^c	27.1	9
Nondetected or Contaminated PMS Stars								
HM 5	270	129	<190	<5390	<165	<470	...	10
UX Cha	114	<150	<1020	<82000	<70	<272	90	
Sz 23	<1000	<1250	≤ 575	≤ 183	...	11
HM 19	≤ 1000	≤ 1550	...	12
VX Cha	<100	<100	<200	<8000	<190	<600	...	13
GK-1	≤ 5500	≤ 22300	...	14

NOTE.—The list also contains the Chamaeleon I targets observed but not clearly detected for comparison. (1) Henning et al. 1993 measured a 1.3 mm flux. We included this star for the purpose of checking calibration of *ISO* fluxes. (2) Indistinguishable from the nearby reflection nebula in the *IRAS* beam. At 60 μm , our observations indicate a point source. At 100 μm , we are only able to place an upper limit to the flux. (3) Henning et al. 1993 measured a 1.3 mm flux. At 60 μm , our observations indicate a point source. At 100 μm , the data appear to be contaminated by flux from the nearby B-type star HD 97048, and we give only an upper limit. (4) Another TTS, CHX 15a falls on one of the source-frame pixels. *IRAS* detected flux from both objects, and we give an upper limit to the contribution from WY Cha. At 60 μm , the total fluxes agree with the *IRAS* value; at 100 μm , cirrus confusion is very high. (5) Originally identified as the source of the far-IR emission detected by *IRAS* at this position. Subsequent X-ray studies questioned this association, and Walter 1992 considered nearby CHX 18N (also WTTs, separation $\sim 24''$) to be the IR source. In our *ISO* observations, the two stars fall on different pixels in the source frame. Both pixels show detected emission, and it seems that each star contributes part of the far-IR emission. (6) This star has surrounding nebulosity. It appears to be a point source at 60 μm but at 100 μm appears either extended or confused with the nebulosity. (7) Henning et al. 1993 measured a 1.3 mm flux. Our measurements at 60 and 100 μm are significantly lower than *IRAS* co-added data. Evidence for either extension or nebulosity confusion at 100 μm . (8) One of the X-ray-selected WTTs (Alcala et al. 1995), and it was one of the few confirmed as PMS by detection of lithium (Covino et al. 1997). (9) X-ray-selected WTTs (Walter et al. 1994). It appears quite extended in our data at both wavelengths. (10) Hartigan 1993 notes that this source has essentially disappeared since its first detection. (11) *IRAS* lists no data for either VW Cha or Sz 23 due to the proximity of the Infrared Nebula. Both stars fall on the same ISOPHOT pixel, and we provide an upper limit to their combined fluxes. (12) Contaminated with flux from nearby PSC 11072–7727, the Infrared Nebula. (13) This source appears to be dramatically variable. While Prusti, Whittet, & Wesselius 1992 give near-IR magnitudes, it went undetected by the recent DENIS observations (Cambresy et al. 1998). (14) Contaminated with flux from nearby HD 97300.

^a Photospheric estimates have not been subtracted from the fluxes presented. Upper limits given are 3σ .

^b From co-added *IRAS* data and DECON (Weaver & Jones 1992).

^c Raster measurement at 90 μm .

vities are much worse than originally anticipated, and as a result, the detection of excesses was somewhat compromised. A complete list of all observed targets with signals and uncertainties is presented in Tables 3 and 4.

A total of 36 targets were detected out of 148 observed. One-third of the detections are in the young Chamaeleon cluster.

4. IR EXCESSES

In order to determine if there is excess emission at the wavelengths observed, a good estimate of the stellar photospheric flux is required. For non-PMS cluster members more distant than the Hyades (46 pc), the photospheric contributions at 60, 90, and 100 μm are negligible compared

to the measured ISOPHOT sensitivities (see § 3). For stars in the Hyades and closer and PMS stars, we estimated the photospheric flux from published *K*-band magnitudes (Alcala et al. 1995; Gauvin & Strom 1992; Lawson, Feigelson, & Huenemoerder 1996; Randich, Schmitt, & Prosser 1996; Walter et al. 1994). Several *K*-band magnitudes were also obtained for us by J. Hare (1997, private communication). Where *K*-band magnitudes were unavailable, we used *V*-band magnitudes and published $V-[12]$ colors (Cohen et al. 1987). A comparison of the results of these two extrapolation methods suggests that the uncertainty in the predicted photospheric values is less than 10%, significantly less than the noise in our measurements.

Of our 36 detected sources, 33 show evidence of excess

TABLE 7
OPEN CLUSTERS AND YOUNG FIELD STARS: *IRAS* PSC AND FSC FLUXES AND NEW PHOTOMETRY OF STARS WITH INFRARED EXCESS

TARGET	<i>IRAS</i> FLUXES				<i>ISO</i> FLUXES ^a		f_d ($\times 10^{-4}$)	NOTES
	12 μm (mJy)	25 μm (mJy)	60 μm (mJy)	100 μm (mJy)	60 μm (mJy)	90 μm (mJy)		
<i>α Persei</i>								
HE 361	<250	<250	<400	<1800	36	<100	6.2	
Pleiades								
HII 1132	224	<240	<280	<2700	28	26	66.0	1
HII 3163	<100	<300	<300	<2000	<70	38	93.4	
Ursa Major								
HD 72905	885	208	<180	<600	77	53	2.8	
HD 125451	717	203	<160	<440	170	<200 ^b	0.77	
HD 139798	497	127	<240	<800	62	<150 ^b	0.33	
HD 184960	605	166	<170	<1100	50	46	1.0	
Coma Berenices								
HD 107067	<110	<270	<280	<700	170	<200 ^b	11.5	2
HD 108102	<150	<210	<240	<600	150	<200 ^b	5.9	
HD 108651	154	<200	<200	<340	177	<200 ^b	1.3	
Hyades								
HD 27459	530	<160	<350	<1000	50	<36	0.95	
Young Field Stars								
HD 105 .....	...	...	...	...	143	167	2.9	
HD 35850	440	80	<180	<1930	49	50	0.26	
HD 37484	120	120	130	<410	115	84	1.6	
HD 134319 .....	...	...	...	...	48	<33	1.6	
HD 177996	220	<170	<170	<830	<72	42	0.47	
HD 202917 .....	...	...	...	...	50	38	2.5	
HD 209253	290	<150	140	<680	127	107	1.0	
Other								
HD 151044	321	73	116	<640	88	100	1.5	3

NOTE.—(1) *IRAS* FSC has a 12 μm measurement that is much too high to be photosphere, though there is no indication that this has ever been identified as an IR excess source. Our own observations with the UCLA double-beam infrared camera at the Lick 3 m Shane telescope show normal magnitudes at *J* and *K* bands for this star's spectral type. (2) The SB nature of this source is unconfirmed. Odenkirchen et al. 1998 note that the *Hipparcos* distance for this object is inconsistent with its photometric distance and placing the star at the cluster distance gives values for its space motion that are more consistent with cluster mean values. (3) Once considered an Ursa Major candidate. Please see text.

^a Photospheric estimates have not been subtracted from the fluxes presented. Upper limits given are 3 σ .

^b Chopped upper limit at 100 μm .

far-IR emission. Basic characteristics of these excess sources including spectral type, *V*-band magnitude, *B*–*V* color, rotational velocity, distance, age, and multiplicity are listed in Table 5.

About one-third of these sources are in young star-forming regions and, based on *IRAS* results, were suspected to have IR excesses. For the most part, only the 12 and 25 μm *IRAS* measurements are reliable, and our new measurements at 60 and 100 μm complement these. Our *ISO* observations demonstrate for the first time that there is excess emission at 60 and 90 or 100 μm for 13 cluster stars, five young field stars, and one other field star. These excess sources are presented in Tables 6 (CTTs and WTTs) and 7 (cluster and field stars) together with *IRAS* measurements and upper limits.

The detections of IR excess are associated with stars of a

range of spectral types and luminosities. For convenience we adopt a parameter that is independent of luminosity to describe systems exhibiting excess emission from circumstellar dust. The fractional excess luminosity, $f_d \equiv L_{\text{ex}}/L_*$, where L_{ex} is the luminosity of dust and L_* is the stellar bolometric luminosity, effectively provides a measure of the relative dust mass for small particles of radius $a \lesssim 1 \mu\text{m}$ in systems with roughly the same dominant temperature. Values of f_d for each of our excess sources were calculated following the method of Backman & Gillett (1987), summing the luminosities in each wavelength band and including a correction to account for excess flux from wavelengths longer than the 90 or 100 μm band: $f_d = [L_{\text{ex}(12)} + L_{\text{ex}(25)} + L_{\text{ex}(60)} + L_{\text{ex}(90\text{or}100)} + c]/L_*$.

IRAS 12 and 25 μm measurements, where available, were used to determine $L_{\text{ex}(12)}$ and $L_{\text{ex}(25)}$. However, for the vast

majority of our targets older than ~ 20 Myr, there was either no measurable excess emission at 12 and 25 μm or no flux measurements available. Values for $L_{\text{ex}(60)}$ and $L_{\text{ex}(90 \text{ or } 100)}$ were derived from the data in Tables 6 and 7. To account for any unmeasured excess emission at wavelengths shorter than 60 μm and longer than 100 μm , we used the values of f_d and the 25, 60, and 100 μm measurements for 14 stars from Table X in Backman & Paresce (1993) and calculated the correction factor necessary to reproduce the final f_d values from only the 60 and 100 μm excesses. This correction factor, $c = 1.85$, was then applied where we had only 60 and 90 or 100 μm data.

5. DISCUSSION

5.1. Cluster Stars

We detected at least one IR excess source in almost every cluster observed. Since the implications of the detections differ by cluster, we review each cluster separately.

Coma Berenices.—Three IR excess sources were detected out of 26 stars observed. While the actual number of detections is small, several characteristics of the cluster and the observations combine to make this a remarkable result. Coma Berenices is a very sparse cluster, comprised of only 42 optically identified members at the time of our observations, 35 of which are of spectral type earlier than K0. It is one of the oldest open clusters we observed, with an age of 500 Myr. Based on the drop-off of f_d with age described in § 5.3, Coma Berenices stars should have values of f_d on average a factor of 100 less than stars in the α Persei cluster. The fact that Coma Berenices at 88 pc is relatively close increases our sensitivity to excess flux there compared to α Persei by a factor of only 4. Furthermore, this cluster could be observed only early in *ISO*'s lifetime when we used the less sensitive chopping mode with 3σ noise limits at least 4 times higher than those of the raster observations. For the three Coma Berenices excess sources to be detectable, they must have values of f_d 10–100 times higher than we would expect, indicating that they are unusual systems. At least three other stars in the cluster display only slightly less than 3σ signals on the center pixel, suggesting the presence of additional excess systems. Only very limited information on the members of Coma Berenices is available. Detailed photometric and spectroscopic observations and FIR data are nearly nonexistent, although there are now Two Micron All Sky Survey (2MASS) observations.

Ursa Major.—Our observations provide the first firm evidence for substantial excesses around stars in the Ursa Major cluster, which has an age ~ 300 Myr and lies at a distance ~ 25 pc. This cluster has two components: the nucleus and stream (Roman 1949). Searches to date, generally involving only the A-type members (Abraham et al. 1998; Lecavelier Des Etangs, Ferlet, & Vidal-Madjar 1997; Skrutskie et al. 1991), produced evidence for only one circumstellar disk (associated with β UMa, a nucleus member) out of 30 separate nucleus and stream systems observed. One of our detected stars, HD 139798, was suggested as a 25 μm excess source by Stencel & Backman (1991), but its status as a possible Ursa Major stream member was not noted. All of our detected excess sources are probable members of the Ursa Major stream. However, all of our observations of the nucleus stars were made early in the *ISO* mission and used the chopping mode, with the lower sensitivity as mentioned above. Two nucleus stars exhibited

emission at a level just less than our 3σ limit indicating that more sensitive long-wavelength observations may reveal additional excess systems.

Pleiades.—Here we detected two very bright sources out of 14 stars observed. While these two excess sources are intriguing, they are not likely to be typical. Considering the relatively young age of the Pleiades, just over 100 Myr, we might expect a large number of sources with $f_d \sim 10^{-4}$. However, for a G5 star, the median spectral type observed in this cluster, the lowest detectable f_d was $\sim 7 \times 10^{-4}$. With decreased sensitivity in many regions of this cluster due to high cirrus, it is not surprising that we detected only the highest f_d disks. We note that, because of *ISO*'s pointing constraints, there was very limited time to observe the Pleiades, resulting in a survey of only a tiny fraction of its members. The potential for detecting additional excess sources in this cluster is high.

Chamaeleon I and Upper Scorpius.—Perhaps the least surprising of the detections are those of the PMS stars in the Chamaeleon I and Upper Scorpius associations. We were able to detect emission from 14 of 33 observed targets. While the vast majority (13) of the detected stars were known previously to be excess sources, most lacked reliable 60 and/or 100 μm fluxes or were confused with other sources. Unfortunately, the resolution of *ISO* was insufficient to resolve three of the CTTs we observed. We detected excess in five of the WTTs we observed. All of the non-detected targets are WTTs and are either highly variable (e.g., VX Cha) or from the X-ray-detected PMS sources (Alcala et al. 1995), many of which were determined to be older stars after our program of observations was executed. Comments on individual sources are in notes to Table 6. Of the two stars observed in Upper Scorpius, one resulted in a very strong detection, over 100 mJy in both the 60 and 90 μm bands. The similarity in appearance to the Chamaeleon sources suggests that there are likely to be numerous excess sources in this cluster yet to be identified. In fact, Backman et al. (1997) reported a significant detection of the sum of emission from six A-type stars in the Sco-Cen association.

α Persei.—In contrast to the preceding clusters, the detection rate in this cluster was disappointing. With an estimated age ~ 50 Myr, α Persei would be expected to contain systems with $f_d \sim 10^{-3}$. Observations of this cluster are complicated by confusion with galactic plane sources as well as a greater distance of 185 pc. Nevertheless, an $f_d \sim$ few times 10^{-4} for an F5 star, the median observed spectral type of this cluster, would be well within our detection limits. However, recent dating of this cluster by lithium depletion boundary methods (Stauffer et al. 1999) yields an age of ~ 125 Myr, more than double the previous estimate. This would reduce our expected f_d by a factor of 4, putting the brighter cluster systems just at our detection limit. If α Persei is as young as first thought, it would be one of the few clusters with ages just older than those of the WTTs, such as in Chamaeleon and Taurus, making it extremely important for characterizing circumstellar disks at this point in their evolution. More sensitive observations and a resolution of the age question are essential for this cluster.

Taurus.—The lack of significant detections in Taurus is also surprising. With an average age of about 25 Myr and at 140 pc, Taurus is comparable to the Chamaeleon cluster and thus would be expected to contain a large number of detectable excess sources. However, time to observe this cluster was limited, and thus statistics are poor. The targets

observed were X-ray-selected WTTs; however, unlike those in Chamaeleon, most Taurus WTTs are confirmed PMS stars (Bouvier et al. 1997).

Hyades.—This cluster, one of the older clusters at 625 Myr, is relatively close at only 46 pc. This is about twice as far and twice as old as the Ursa Major cluster, where our detected f_d values are on the order of 10^{-4} . For the Hyades we expect f_d to be on the order of 10^{-5} , right at our detection limit for an F5 star, the median spectral type observed in the Hyades. Thus, typical disks could have escaped detection. Again, observing time on this cluster was limited and we observed only a small percentage of cluster members. More sensitive observations are necessary to determine the true incidence of IR excess.

5.2. Young Field Stars

For most of these stars, ages were taken from the literature (see Table 2). In a few cases, ages were unavailable or unconfirmed. Chromospheric activity is a useful age indicator for young, low-mass stars and can be measured by the brightness of the Ca II core reversal. This reversal is often measured by the so-called S -parameter (Duncan et al. 1991; Henry et al. 1996 and references therein). The S -parameters for two stars, HD 35850 and HD 209253, were measured with the 0.6 m coude auxiliary telescope and the Hamilton echelle spectrograph at Lick Observatory by Silverstone (2000). These data were calibrated by measuring stars in common with Duncan et al. (1991) and Henry et al. (1996). Ages (Table 2) were calculated following the method of Duncan et al. (1991).

Among the young field stars, we find detectable excesses in seven out of the 19 stars observed. The values of f_d for these excess stars are comparable to those of some members of the open clusters, but distances to these two samples are very different. On average, the young field stars are at 45 pc and have an age of 200 Myr, making them most analogous to the Ursa Major cluster, where there was also a significant number of detections. A greater percentage of young field star observations than the Ursa Major observations used the high-sensitivity raster mode.

The S -parameter was also measured for the star HD 151044, an Ursa Major stream candidate ($\approx 3 \times 10^8$ yr) (Boesgaard et al. 1988). However, its membership has been questioned on the basis of relatively low chromospheric emission and similar but not entirely consistent space motion with the Ursa Major stream (Soderblom & Clements 1987; Soderblom & Mayor 1993). Our new chromospheric activity age, 2.8×10^9 yr, is consistent with HD 151044 being too old to be part of the Ursa Major stream. However, the calculated excess seems extreme if the star is so old.

5.3. The Age- f_d Correlation

As defined above, f_d is the fractional dust luminosity, L_{ex}/L_* . For each cluster and for the young field stars as a whole, an average f_d was calculated as follows: the sum of all values for f_d from detections and nondetections, including negative values, was divided by the total number of targets observed. Negative values for f_d resulted when the observed flux was less than the photospheric flux estimate, and in all the approximately 40 cases, the “negative excess” was less than the 3σ noise level. The Chamaeleon I sources were separated into two groups because of the wide relative age spread of the stars. The division was set at 10 Myr, resulting

in groups of nearly equal size. However, whether Chamaeleon I is plotted as one group or two, the effect on the fitted age- f_d relation is negligible.

Figure 1 shows the averaged f_d values versus the cluster ages. Comparable values for a few nearby Vega-type stars are plotted over the main cluster results in Figure 2. There is clear evidence for a systematic decrease in the fractional IR excess emission with stellar age. A regression fit to the cluster data yields a reasonably good fit with a power law of the form $f_d \propto (\text{age})^{-1.76}$. This is consistent with sub-

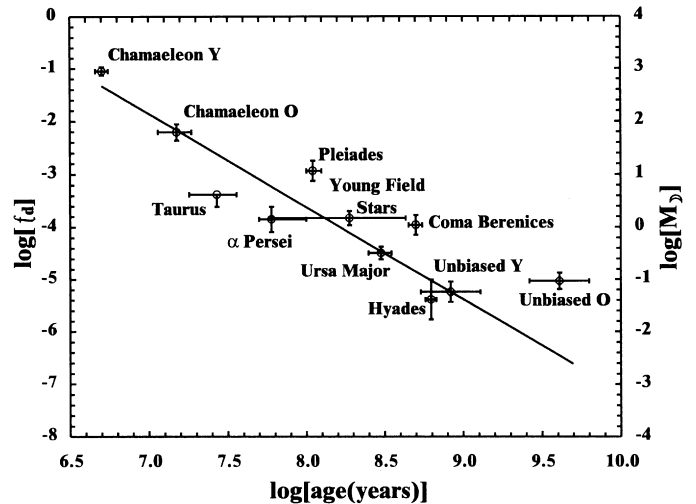


FIG. 1.—Behavior of f_d with stellar age. Cluster ages are taken from the literature (see Table 1). The plotted line is a regression fit to the data with slope ≈ -1.76 . Plotted points represent an average f_d for each cluster that includes both detections and nondetections. Vertical error bars represent the standard deviation of the average. The two points “Unbiased Y” and “Unbiased O” are from Silverstone (2000) and are not included in the calculation of the regression.

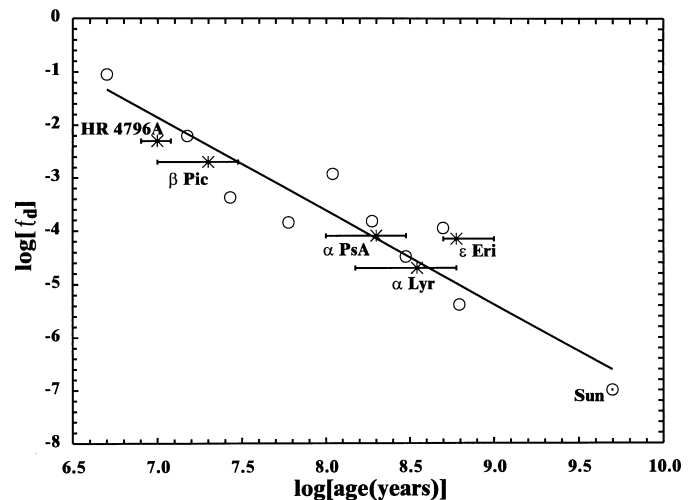


FIG. 2.—Archetypal Vega phenomenon stars (asterisks) and the Sun are overplotted on the cluster points (open circles) for comparison (Soderblom & Dappen 1989; Jura et al. 1998; Barrado y Navascues et al. 1999; Holland et al. 1998 and references therein). The position of the Vega-type stars may be regarded as representing a rough upper envelope of f_d at a given age. The value of f_d plotted for the Sun is based on emission from zodiacal dust only (≤ 5 AU) and does not include the unknown contribution from outside the orbit of Neptune, which could or could not be significant.

millimeter studies of Pleiades, Ursa Major, Taurus, and field stars by Zuckerman & Becklin (1993), who found dust mass $\propto (\text{age})^{-2}$. In contrast, Habing et al. (2001) have recently proposed that the majority of circumstellar disks disappear after the first 400 Myr based on their detection of only a few disks around field stars with ages greater than 400 Myr. While it is difficult to compare the two sets of observations directly because of differing target samples and noise levels, we detect excess emission from dust around seven stars with ages greater than 400 Myr, showing that disks do persist beyond 400 Myr though the amount of dust tends to decline.

Since f_d is a measure of the emission from circumstellar dust, it should be correlated with the mass of dust (see also Zuckerman & Becklin 1993). Silverstone (2000) provides an approximate conversion relation, dust mass = $f_d(1.4 \times 10^4) M_{\text{moon}}$, where M_{moon} is the mass of the Moon. Masses calculated in this way lead to the right-hand axis in Figure 1.

The power-law index near -2 in the age–dust mass relationship can possibly be explained by a simple model of collisionally replenished secondary dust disks. If the dust-clearing timescale is shorter than the age of the system, the amount of secondary dust will be determined by the instantaneous collisional rate of large particles. The typical dust-clearing timescales are given by Backman & Paresce (1993) and Silverstone (2000) and are less than 10^7 yr. The collisional rate of large particles dN/dt should go as N^2 , where N is the number density of large planetesimals, comets, or asteroids in the system. Thus,

$$f_d \propto \frac{dN}{dt} \propto -N^2. \quad (1)$$

In addition, it is expected that the loss of large particles will be determined by the same collisional type process such that, integrating equation (1), we find that the number of large particles will decrease with time as

$$N \propto \frac{1}{t}. \quad (2)$$

Combining equations (1) and (2), we get that the mass of emitting dust is given by

$$M(\text{emitting dust}) \propto f_d \propto \frac{dN}{dt} \propto N^2 \propto \frac{1}{t^2}. \quad (3)$$

This is similar to the observed power-law falloff. The problem can also be reversed. The fact that we observe the mass of emitting dust dropping off as $1/t^2$ suggests that in this model, the number of large particles N , in planetesimals, comets, and asteroids, falls as $1/t$ independent of the mechanism that produces the falloff.

5.4. Correlations with Other Stellar Characteristics

With only a small number of detections in each cluster, it is difficult to draw general conclusions regarding the relationship between circumstellar material and stellar characteristics such as multiplicity and rotation. We detected dust around single stars; several spectroscopic binaries, including all three Coma Berenices excess stars and one young field star, HD 177996; and one wide binary, HD 125451 (separation ~ 4000 AU). Therefore, over the age range of 10–600 Myr the presence of a stellar companion does not necessarily preclude the existence of associated

circumstellar material. Osterloh & Beckwith (1995) and Jensen, Mathieu, & Fuller (1996) show that disks may surround members of binary systems in cases in which the separation is either less than 1 AU or greater than 100 AU.

The detected sources exhibit a wide range of rotational velocities. In the young open clusters, half our detected excess sources have $v \sin i$ less than the median rotational velocity of their parent clusters. This distribution is similar to the $v \sin i$ distribution in the original sample of targets. In each cluster about half of the targets had $v \sin i$ less than the median rotational velocity of the cluster. Only in the Pleiades is there a significant imbalance; there the two detected sources have the highest $v \sin i$ of the stars we observed in that cluster, roughly 5 times the cluster median. Among the young field stars, those detected have a range of rotational velocities similar to the young open clusters (including both slow rotators and stars with rotational velocities similar to the two detected Pleiades stars). A dearth of comprehensive data for rotational velocities of the PMS stars in Scorpius and Chamaeleon I prevents detailed discussion of these samples.

Most of our detections in the young open clusters and young field stars (i.e., not PMS stars) are stars of spectral type F. This is partly due to selection effects: we observed a large fraction of F-type stars, and dust around F-type stars would be easier to detect because of the higher luminosity than G- or K-type stars. For F-type stars alone, we detect excess IR emission in 12 out of 48 stars observed, or 25%. In their review, Lagrange et al. (2000) state for stars of spectral types A–K that the fraction with disks is 15%. While the fraction for F-type stars specifically is not noted, our results suggest that the fraction is indeed significantly higher than 15%. Our results also indicate that future work is likely to confirm a similarly higher percentage for G- and K-type stars.

6. SUMMARY

A survey of almost 150 PMS and young main-sequence stars, the majority of which are members of young open clusters, has been carried out with ISOPHOT. Excess emission at 60, 90, and/or 100 μm , presumably from circumstellar debris disks, has been detected from 33 of the observed stars. The detections are distributed among the observed clusters/groups. A total of 20 of the stars, most of which are of spectral type F, were not previously known to exhibit excess emission and represent a new set of Vega-type systems. Other *ISO* programs of observations with similar objectives to ours (Robberto et al. 1999; Habing et al. 2001) have resulted in much lower detection rates. Much of this can be attributed to greatly different observing strategies, including shorter integration times, method of measuring background, and choice of targets. Because of the differences in observational techniques, it is difficult to compare the results.

A major conclusion from our observations is how the excess IR emission evolves with time. The ratio of excess IR luminosity to stellar luminosity, f_d , appears to drop off with age according to the power law $f_d \propto (\text{age})^{-1.76}$. A power law $f_d \propto (\text{age})^{-2}$ is expected for collisionally replenished secondary dust disks. We do not see evidence for an abrupt cessation of the debris disk phenomenon as reported by Habing et al. (2001).

The detection of the new IR excess sources reported here is only the beginning. More work needs to be done to help

characterize the spectral and spatial extent of systems that have been detected. We have no $100\ \mu\text{m}$ measurements for any of the young cluster stars that we observed in the chopping mode. Many of the PMS objects we measured at $100\ \mu\text{m}$ are not well characterized spatially. We expect that the Deep Near Infrared Survey of the Southern Sky (DENIS) and 2MASS searches will add near-IR data to many of the young cluster sources but may not be able to measure some of the more distant stars. Observations of our new excess sources are also needed in the $10\text{--}60\ \mu\text{m}$ region. However, the far-IR wavelengths at which dust disks are most readily studied are inaccessible from the ground, requiring future high-altitude and space missions, such as SOFIA and *SIRTF*. Finally, the multiplicity of a number of these sources, both young cluster and PMS, needs to be better established.

Our results indicate that there is great potential for more sensitive space-based studies of clusters to identify addi-

tional solar-type stars with far-IR excess. The detection and analysis of many more of these intriguing objects will provide a better understanding of the planet formation process.

The ISOPHOT data presented in this paper were reduced using PIA, which is a joint development by the ESA Astrophysics Division and the ISOPHOT consortium. This work was facilitated by the use of the Vizier service and the SIMBAD database developed at CDS. This work has made use of XCATSCAN, an internet service provided by the Infrared Processing and Analysis Center (IPAC), which is operated by the Jet Propulsion Lab and the California Institute of Technology under contract to NASA. We would like to thank M. Jura and P. Goldreich for assistance with the original *ISO* program and D. Backman for helpful comments. This research was supported in part by an *ISO* Key Project NASA grant to UCLA and Caltech.

APPENDIX

FLUX CALIBRATION

As discussed by Spangler et al. (1999) and Silverstone (2000), a number of targets from our entire *ISO*:DEBRIS program had existing *IRAS* Faint Source Catalogue (FSC) measurements at $60\ \mu\text{m}$ that were confirmed to be stellar in origin. We made use of these data to check the PIA/FCS calibration of our ISOPHOT fluxes. The comparison of 24 sources is plotted in Figure 3, along with the line $F_{ISO} = F_{IRAS}$ for reference, and shows good agreement between the *IRAS* FSC and *ISO* FCS flux measurements.

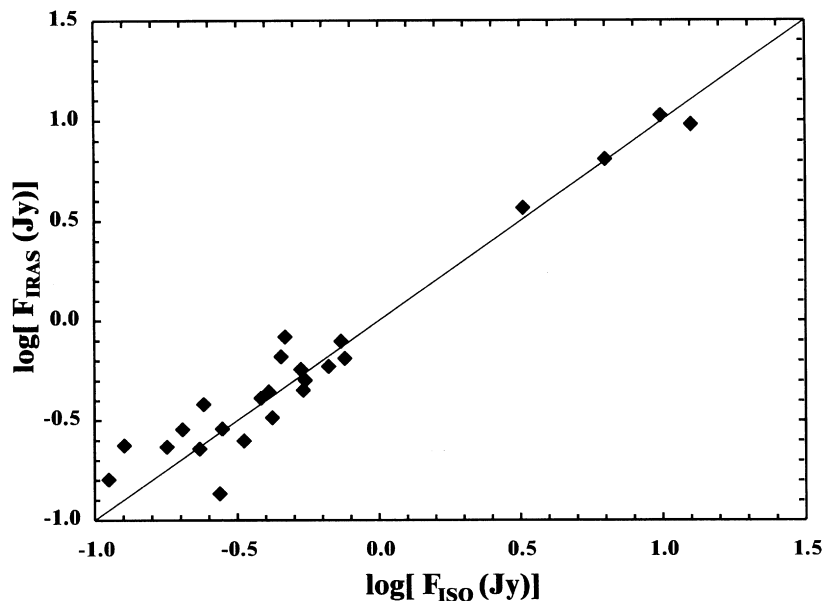


FIG. 3.—Comparison of our calibrated *ISO* $60\ \mu\text{m}$ observations to *IRAS* FSC flux densities. The line $F_{ISO} = F_{IRAS}$ is plotted for reference.

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