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AGE DEPENDENCE OF THE VEGA PHENOMENON: OBSERVATIONS

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ABSTRACT

We study the time dependency of Vega-like excesses using infrared studies obtained with the imaging photopolarimeter ISOPHOT on board the *Infrared Space Observatory*. We review the different studies published on this issue and critically check and revise ages and fractional luminosities in the different samples. The conclusions of our study differ significantly from those obtained by other authors (e.g., Holland and coworkers; Spangler and coworkers), who suggested that there is a global power law governing the amount of dust seen in debris disks as a function of time. Our investigations lead us to conclude that (1) for stars at most ages, a large spread in fractional luminosity occurs, but (2) there are few very young stars with intermediate or small excesses; (3) the maximum excess seen in stars of a given age is about $f_d \approx 10^{-3}$, independent of time; and (4) Vega-like excess is more common in young stars than in old stars.
Subject headings: circumstellar matter — infrared: stars

1. INTRODUCTION

The detection of dust orbiting around Vega (Aumann et al. 1984) and other nearby main-sequence stars by the *IRAS* satellite marks the first detection of planetary material in stellar systems other than our own solar system. In the years since then, much attention has been paid to understanding the origin and evolution of this phenomenon and to determining if and how this discovery can tell us more about the planetary systems probably hidden in those dust rings and clouds. One important aspect of the research was the study of temporal evolution of the amount of dust present in these systems. Already Backman et al. (1987) noticed from color-color studies that systems such as Vega, Fomalhaut, and ϵ Eridani could be more developed versions (with less dust) of the most famous Vega-like star, β Pictoris. This suspicion was further strengthened by submillimeter observations of the four main members of this class of objects. Submillimeter observations are very useful, since they have a better chance of measuring the mass present in the system. Holland et al. (1998) showed that the measured masses of the disks of several prominent Vega-like stars seem to follow a power-law dependence with time. A stunning extra was that even the zodiacal dust cloud of the solar system seems to fit this trend.

With the launch of the *Infrared Space Observatory* (*ISO*) in 1995, several research groups set out to get a better handle on the time evolution of the Vega phenomenon. These groups used observations similar to the ones obtained with *IRAS*, namely, photometry at mid- to far-IR wavelengths to determine the dust masses in these systems. Several roads where followed to improve the poor statistical significance of the *IRAS* studies: *IRAS* had shown that some stars display the Vega phenomenon, but the stars did not form a good sample in several ways. First, the ages of the stars were poorly determined. Second, the detection limits of *IRAS* were such that large excesses could be detected, but for most stars the detection of the photosphere of the stars was not possible. It was therefore easier to establish that a star has a dust disk than to show that it does not have one.

The first issue, concerning the age determination, was addressed by several groups (e.g., Spangler et al. 2001) by choosing stars in different clusters. Since the ages of clusters can be determined rather accurately, this strategy should provide a much better calibration of the time axis. The disadvantage of this approach was that most clusters are not very nearby, and the photosphere of most stars in the sample was out of reach also for *ISO* sensitivities.

Habing et al. (1999, 2001) and Silverstone (2000) addressed the second problem of the *IRAS* results on the presence of a debris disk. They selected volume-limited samples of stars in order to study the Vega phenomenon in field stars. In particular, they chose different volumes for stars with different spectral type (i.e., luminosity) in order to ensure that the photosphere of the star would be detectable in all cases with a good signal-to-noise ratio. This sample is therefore mainly geared to check whether or not a disk is present. The obvious problem with field stars is, of course, that it is much more difficult to determine accurate ages for these stars, which may make a time-dust mass relation difficult to discover.

After the launch of *ISO*, it turned out that the targeted photometric sensitivities were difficult to reach. In fact, the limits could be reached, but only with a changed observational strategy (mini-maps) that required much more time than foreseen in the proposals. This has made the outcome of the studies less decisive than had been hoped. The task of cleaning up this question will be one of *SIRTF*'s major goals. Observers were faced with the decision to either accept larger limits or to observe fewer sources and/or at fewer wavelengths.

Nevertheless, the groups working with *ISO* came up with age trends based on their observations. Studying the disk frequency around young A stars, Habing et al. (1999, 2001) concluded that there was a very clear break in the presence of a debris disk around 400 Myr. Most A stars younger than this limit showed Vega-like IR excesses, while most A stars older than this limit did not show corresponding excesses. However, this work and the work of Decin et al. (2000) also showed that several stars supposedly much older did also show IR excesses.

Spangler et al. (2001) published the results of two samples: stars in several clusters of various ages and a number of field stars with less well determined ages. In their data, Spangler et al. (2001) could determine a trend in the time evolution of the dust content of stellar systems. They found a power-law dependence with a power $f_d \propto t^{-1.76}$. They further argued that a collisional cascade is expected to produce a t^{-2} dependence, and given the errors in the data, that might well be just what is observed.

However, there are two reasons to doubt the conclusions reached by Spangler et al. (2001): (1) the observed relation between dust mass and age is not confirmed when large samples are considered, and (2) the expected relation between age and dust mass as derived by Spangler et al. (2001) omits some important physical effects. In this paper, we reanalyze observations of IR excess from Vega stars, and in a forthcoming paper (Dominik & Decin 2003, hereafter Paper II) we will reformulate the theory for the time dependence of dust mass from debris disks. We argue that the current observational evidence for the occurrence of this power law is still very weak. First, in the cluster observations, this result is based on very small number statistics: usually there was only one excess source detected per cluster (with a maximum of three). Furthermore, in order to arrive at a representation of the *average* dust content of stars in a cluster, Spangler et al. (2001) average all the derived excesses. Because of the relatively low S/N in the observations, they also include in this calculation "negative" excesses. It is clear that such an approach can have big problems when small numbers are involved. In particular, if only one source in each cluster has a clearly detectable excess, the procedure described above would dilute the measured IR excess. The average dust mass then depends on the number of observed stars in a certain cluster. Since this number varies per cluster, strong systematic effects are to be expected. A better approach would be to look only at the sources with clearly detected excesses. If there is a power-law time dependence intrinsic to these sources, then it should also be visible by just looking at the strongest excess stars of each age. Finally, Spangler et al. (2001) included in their plots also points obtained for the Chamaeleon I, Scorpius, and Taurus star-forming clouds. These stars are clearly pre–main-sequence objects with first-generation disks in which the formation of larger bodies is incipient, while the dust in debris disks is thought to be replenished by collisions of, e.g., comets. Moreover, the disks in pre–main-sequence stars are often optically thick in the radial direction, so that the IR luminosity in such sources is determined by the geometry of the disk (flaring or nonflaring, for example) and not by the dust mass in the disk. These stars should therefore be excluded when considering the evolution of second-generation dust.

The purpose of this study is to reinvestigate the time dependence of Vega-like excesses from photometric studies with the *ISO* satellite. The paper is organized as follows. A list of stars with IR excess detected by the *ISO* satellite is compiled in § 2 and a critical assessment of the determinations of age and IR-to-total fractional luminosity is made. In the following section we plot the fractional luminosity versus age for various samples and discuss these diagrams in the framework of the hypotheses alluded to in this introduction. In § 4 we discuss the results and derive lessons and challenges for the coming *SIRTF* observations.

2. PARAMETER DETERMINATION

The data we discuss in this paper were taken from Habing et al. (1999, 2001), Decin et al. (2000), Silverstone (2000), and Spangler et al. (2001) and G. Decin et al. (2004, in preparation). They all concern stars with an IR excess which is most probable caused by dust in a stellar disk and were obtained with ISOPHOT, the imaging photopolarimeter on board *ISO* (Klaas et al. 1994; Kessler et al. 1996). All data in the samples of Habing et al. (1999, 2001) and Decin et al. (2000) are C100 mini-maps at 60 μm, while the samples of Silverstone (2000) and Spangler et al. (2001) consist of a mixture of mini-maps and chopped C100 observations. In order to limit the discussion to debris disks and not to pollute the sample with first-generation disks, we only consider stars older than 10 Myr.

2.1. *Age Determination*

A variety of observational tests, which are based on different physical phenomena and can be applied to different stellar types with varying success, have been formulated to determine the age of main-sequence stars. The dating of open clusters is considered most reliable, e.g., by fitting the cluster member stars' location on Hertzsprung-Russell diagrams to models of stellar evolution. This method is used for most stars in the sample of Spangler et al. (2001). The disadvantage of this approach for our purposes is that most clusters are far away, so that only disks with large excesses can be securely identified, while small excesses will be difficult to distinguish from photospheric fluxes.

The other groups worked with single field stars, which more difficult and uncertain age determinations (Decin et al. 2000; Habing et al. 2001; Silverstone 2000, and some stars of Spangler et al. 2001). An analysis of the different methods used for age determination for main-sequence stars was done by Lachaume et al. (1999). They concluded that isochrones are the best age estimators for stars with spectral type in the range B9–G5. A reliable age determination depends not only on the accuracy of the temperature and the luminosity determination, but also on that of the metallicity. Since stars evolve faster when they age, accurate age determinations are often more difficult for stars that are still close to the zero-age main sequence (ZAMS). A far-reaching ambiguity might arise when it is not clear whether a star is evolved or still in the pre–main-sequence phase of evolution. A famous case is β Pic: from isochrones it was suggested that it may be 280 Myr old. More recently, the discovery of several young M dwarfs that are in a moving group with β Pic has shown that 15 Myr (Barrado y Navascués et al. 1999) is, in fact, a more likely age for this star, as was suggested by Lanz, Heap, & Hubeny (1995).

For late-type stars, Lachaume et al. (1999) concluded that a variety of methods (metallicity, rotation, calcium emission lines, and kinematics) is recommended, with a preference for age determination using stellar rotation. However, many stars require a combination of different methods to properly bracket their actual age. Besides the example given above of β Pic, the age of, e.g., HD 207129 was in dispute for several years. While Jourdain de Muizon et al. (1999) deduced a lifetime of 4.6 Gyr based on the weakness of the Ca II K-line emission, Zuckerman & Webb (2000) found an age estimate of $\sim$40 Myr, relying on space motions and location in space.

All stars under study were subject to the same strategy to obtain a reliable age determination. Priority is given to ages determined by the lifetime of the cluster or moving group to which the star belongs. When it is not known whether a star is a member of a moving group or cluster, and the star is an element of a binary system for which both stars can be placed on the Hertzsprung-Russell diagram, the age as determined by isochrone fitting is taken. When neither of these two conditions is met, and additionally the star is not on the ZAMS and has a spectral type between B9 and G5, then we prefer isochrone fitting to determine the age. Otherwise, the age as determined from rotation or chromospherical activity is taken.

2.2. *Fractional Luminosity*

The second parameter needed in our relationship is the fractional dust luminosity,

$$f_d \equiv F_{\rm bol}^{\rm exc}/F_{\rm bol}^{\rm photosp} = L^{\rm dust}/L^{\rm bol}\ , \qquad (1)$$

which is a commonly used measure of the amount of dust in these systems.

The different groups adopted different criteria for considering an object as displaying an excess. Decin et al. (2000) and Habing et al. (2001) accepted only measurements in which both the detection itself and the excess are measured with $S/N \gtrsim 3$; here the noise is calculated as the Gaussian dispersion of the excess around zero for the nonexcess stars, leading to a dispersion of $\sim$30 mJy at 60 μm. Spangler et al. (2001) considered a source as detected if the flux at the on-target (center) pixel exceeded 3 times the standard deviation of the flux on the eight surrounding pixels; they obtained a standard deviation comparable with Decin et al. (2000) and Habing et al. (2001); however, an excess is accepted when it has an $S/N \gtrsim 1$. Silverstone (2000) used the same standard deviation calculation as Spangler et al. (2001), but used an $S/N \gtrsim 2$ criterion for the detection itself and for the excess measurement. To have a more consistent sample, we have refined the sample of Spangler by requiring an S/N of the excess larger than 2; this led to the discarding of four objects.

The determination of the fractional luminosity, f_d, is, in principle, straightforward if the excess radiation emitted by the dust can be measured at enough wavelengths. However, if the dust flux is measured at only one or a few points, one needs to make some assumption about the shape of the dust emission spectrum. While Decin et al. (2000) and Habing et al. (2001) derived the fractional luminosity based on the excess measurement at 60 μm, making an assumption about the temperature of the dust as well, Spangler et al. (2001) and Silverstone (2000) calculated values of f_d for each of their excess sources 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. However, for the vast majority of their targets older than $\sim$20 Myr, there was either no measurable excess emission at 12 and 25 μm or no flux measurement available. Therefore, they calculated a correction factor necessary to reproduce the final f_d values from only the 60 and 100 μm excess, based on stars for which flux measurements at different wavelengths were known. Both methods give similar results, except for two stars from Spangler's sample, where their method led to an extremely high value for the fractional luminosity compared with the other method and compared to the results for similar stars. For both stars the fractional luminosity as obtained by the method of Decin et al. (2000) and Habing et al. (2001) is used during further discussion in this paper.

2.3. *Overview of the Results*

In this section, we report on the results of the determination of ages and fractional luminosities for the objects of the five samples considered. All results are summarized in Table 1.

Habing et al. (2001).—This sample was selected from the catalog of stars within 25 pc of the Sun by Woolley (1970) and contained those main-sequence stars (spectral type A through K) for which the photospheric flux at 60 μm is above the ISOPHOT detection limit (30 mJy). The sample was also restricted to those stars for which the infrared flux density can be unequivocally attributed to the target star. From a list of 84 main-sequence stars, 14 stars were found having a 3 σ infrared excess, which is exactly the same fraction as in the G dwarf sample of Decin et al. (2000). From the final list with stars with an IR excess, 55 Cnc is omitted as Vega-type star because the submillimeter flux, initially attributed to dust orbiting the star (Dominik et al. 1998), is reported instead to be from nearby background sources (Greaves et al. 2000).

The ages were estimated by Lachaume et al. (1999) using isochrones for the early-type stars and stellar rotation or a combination of methods for late-type stars. Since then, these determinations have been questioned for two objects of the sample that appear to belong to moving groups of considerably shorter age. As already mentioned, Barrado y Navascués et al. (1999) associated β Pic with several comoving young M dwarfs, the age of which they estimated at 15 Myr. From a more extensive study of this moving group, Zuckerman et al. (2001) lowered this age to the 12 Myr we adopt in this study. Zuckerman & Webb (2000) suggested that HD 207129, too, belongs to a young moving group, the Tucanae association, for which they estimate the age at 40 Myr, i.e., 2 orders of magnitude less than the result of the isochrone and the Ca II study by Lachaume et al. (1999). In support of their shorter age for HD 207129, which we also

TABLE 1

Stellar Parameters for Stars Whose IR Excess Is Most Probably Due to a Debris Disk

Name	V (mag)	$B-V$ (mag)	Parallax (mas)	Spectral Type	log age$_{\rm published}$ (yr)	log f_d	log age$_{\rm revised}$ (yr)	Age Reference	Original ISOPHOT Paper	Reliability Indicator
HD 10647	5.52	0.551	57.63	F8 V	9.54	−3.27	9.54	1	1	1
HD 20794	4.26	0.711	165.02	G8 V	9.86	−4.70	9.86	1	1	1
HD 22484	4.29	0.575	72.89	F9 V	9.72	−4.93	9.72	1	1	1
HD 41700	6.35	0.517	37.46	G0 IV–V	9.63	−3.75	9.63	1	1	1
HD 53143	6.81	0.786	54.33	K0 IV–V	8.99	−3.25	8.99	1	1	1
HD 10700	3.49	0.727	274.17	G8 V	9.86	−4.60	9.86	2	2	2
HD 17925	6.05	0.862	96.33	K1 V	7.90	−3.90	7.90	2	2	2
HD 22049	3.72	0.880	311.00	K2 V	8.51	−3.54	8.51	2	2	1
HD 30495	5.49	0.632	75.10	G3 V	8.32	−4.10	8.32	2	2	1
HD 38678	3.55	0.104	46.47	A2 Vann	8.57	−4.70	8.57	2	2	1
HD 95418	2.34	0.033	41.07	A1 V	8.56	−5.00	8.56	2	2	1
HD 102647	2.14	0.090	90.16	A3 Vvar	8.38	−4.80	8.38	2	2	1
HD 128167	4.47	0.364	64.66	F3 Vwvar	9.23	−5.00	9.23	2	2	1
HD 139664	4.64	0.413	57.09	F5 IV–V	9.05	−4.00	9.05	2	2	1
HD 172167	0.03	−0.001	128.93	A0 Vvar	8.54	−4.80	8.54	2	2	1
HD 207129	5.57	0.601	63.95	G2 V	9.78	−3.80	7.60	6	2	4
HD 216956	1.17	0.145	130.08	A3 V	8.34	−4.30	8.34	2	2	1
β Pic	3.85	0.170	51.90	A3 V	8.45	−2.82	7.08	7	2	4
HE 361	9.68	0.430	...	F4 V	7.70	−3.21	7.70	3	3	4
H II 1132	9.43	0.500	...	F5 V	8.07	−3.37[a]	8.07	3	3	4
HD 72905	5.63	0.618	70.07	G1.5 Vb	8.48	−4.69[a]	8.48	3	3	4
HD 125451	5.41	0.385	38.33	F5 IV	8.48	−4.11	8.48	3	3	4
HD 139798	5.76	0.353	27.98	F2 V	8.48	−4.48	8.48	3	3	4
HD 107067	8.69	0.523	14.54	F8	8.70	−2.85	8.70	3	3	4
HD 108102	8.12	0.534	9.34	F8	8.70	−3.23	8.70	3	3	4
HD 108651	6.63	0.212	12.66	A0p	8.70	−3.89	8.70	3	3	4
HD 105	7.51	0.595	24.85	G0 V	8.67	−3.37	7.93	8	3, 4	4
HD 35850	6.30	0.553	37.26	F7 V:	8.37	−4.52	7.08	9	3, 4	1
HD 134319	8.40	0.677	22.59	G5	8.70	−3.48	8.78	8	3, 4	4
HD 151044	6.47	0.503	34.00	F8 V	9.10	−4.17	9.68	11	3, 4	1
HD 202917	8.65	0.690	21.81	G5 V	8.20	−3.33	7.93	8	3, 4	4
HD 209253	6.63	0.504	33.25	F6/F7 V	8.60	−3.82	8.65	11	3, 4	2
HD 4614	3.46	0.587	167.99	G0 V SB	8.60	−5.43	9.60	10	4	3
HD 131156	4.54	0.720	149.26	G8 V+K4 V	8.90	−5.02	9.30	10	4	3
HD 144284	4.01	0.528	47.79	F8 IV–V	9.10	−5.57	9.49	11	4	2
HD 152391	6.65	0.749	59.04	G8 V	9.00	−4.30	9.00	4	4	1
HD 165341	4.03	0.860	196.62	K0 V SB	9.20	−5.00	9.20	4	4	1
HD 8907	6.66	0.505	29.26	F8	8.76	−3.62	9.48	11	4	1
HD 15115	6.79	0.399	22.33	F2	8.70	−3.35	8.70	4	4	1
HD 15745	7.47	0.360	15.70	F0	8.90	−2.89	8.90	4	4	2
HD 22128	7.59	0.378	7.06	A5	8.50	−3.18	9.14	11	4	1
HD 25457	5.38	0.516	52.00	F5 V	8.70	−4.07	7.93	8	4	4
HD 38207	8.47	0.360	...	F2 V	8.60	−3.00	8.60	4	4	1
HD 164249	7.01	0.458	21.34	F5 V	...	−2.89	7.08	9	4	4
HD 206893	6.69	0.439	25.70	F5 V	8.90	−3.66	8.90	11	4	2
HD 221853	7.35	0.405	14.04	F0	8.90	−3.32	9.25	11	4	2
HD 177817	6.00	−0.025	3.65	B7 V	8.00	−4.19	8.40	11	4	2
HD 3627	3.27	1.268	32.19	K3 III	9.50	−4.46	9.50	5	5	1

[a] Values presented in this paper.

References.—(1) Decin et al. 2000. (2) Habing et al. 2001. (3) Spangler et al. 2001. (4) Silverstone 2000. (5) Decin et al. 2004, in preparation. (6) Zuckerman & Webb 2000. (7) Barrado y Navascués et al. 1999. (8) Montes et al. 2001. (9) Zuckerman et al. 2001. (10) Fernandes et al. 1998. (11) This work.

adopt, Zuckerman & Webb (2000) mention, besides the kinematic evidence, high lithium abundance and an X-ray luminosity that is 10 times that of the Sun.

Decin et al. (2000).—This sample was selected from the CORALIE planet search program and consists mainly of G dwarfs (Udry et al. 2000). The CORALIE distance criterion locates the chosen stars in the Local Bubble, reducing the possibility that the dust responsible for excess thermal emission originates from the interstellar medium rather than from a planetary debris system. Decin et al. (2000) found five excess stars with an $S/N \geq 3$ out of the 30 measured targets. Since the sample selection was free from bias with respect to infrared excess, this work suggests that some 17% of G dwarfs possess debris disks.

Since a fairly conservative approach was used for the selection of the excess stars, we are confident that the fractional luminosities were determined reliably. The ages were estimated from isochrones and confirmed—when possible—by other methods. There is no indication that any of these stars is particularly young. Four objects occur rather close to the ZAMS in the H-R diagram, so that their ages determined from isochrones may be rather uncertain, but the star HD 22484 is definitely well evolved. The fact that a sizeable fraction of a fairly unbiased sample of G dwarfs displays excesses strongly suggests that relatively massive debris disks may survive around main-sequence stars of several Gyr old.

Spangler et al. (2001).—The targets in this sample fall into three distinct categories: (1) Main-sequence stars in relatively nearby (generally closer 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. (3) A small sample of relatively nearby (closer than 60 pc) isolated stars with indications of youth. As mentioned above, the sample of the T Tauri stars is rejected from our study. We want to be sure that the dust is clearly " second generation," i.e., not primordial but released from larger bodies, such as asteroids and comets. Four more objects (HII 3163, HD 17796, HD 184960, and HD 27459) were discarded, because the S/N of the claimed excess measurement is lower than 2.

As alluded to in the previous section, the fractional luminosity of HII 1132 (Pleiades cluster) and HD 72905 (Ursa Major cluster) were adapted to lower values. In total, there were three excess detections in both Coma Berenices and Ursa Major, one detection in both the α Persei and the Pleiades clusters, and no detections in the Hyades. The fraction of excess stars discovered in these clusters is smaller than in the field, probably mainly reflecting the different sensitivity limits of the surveys. The nearby field stars with an IR excess considered by Spangler et al. (2001) amount to seven: HD 105, HD 35850, HD 37484, HD 134319, HD 151044, HD 202917, and HD 209253.

Age determinations for cluster objects can be considered robust. For HD 37484, the age was determined using the abundance of lithium as measured by Favata et al. (1993) in comparison with the lithium abundances of stars in the Taurus, Hyades, and Pleiades clusters. An extrapolation is, however, necessary for this star, which makes the age determination very inaccurate. This star might, in fact, be a pre–main-sequence star (Favata et al. 1993). For all these reasons, this star is omitted from the final sample. As dating technique for the other field stars, Spangler et al. (2001) used literature values of the chromospheric emission as measured in the cores of the Ca II H and K lines. Since significant additional information is available for all six stars, we have reconsidered their age determination.

A literature study shows that four of them are members of moving groups or association: HD 105 and HD 202917 belong to the Local Association (Montes et al. 2001) which is 20–150 Myr old; HD 35850 is a member of the β Pictoris moving group (Zuckerman et al. 2001), which is 12 Myr old. HD 134319 is an element of the Hyades supercluster (600 Myr) (Montes et al. 2001). With respect to the calcium ages, we then find that HD 105 and especially HD 35850 are much younger, while the difference are smaller for the two other stars.

Following Lachaume et al. (1999), we checked the ages for the two remaining field stars, which have a spectral type between B9 and G5, using isochrones by Claret (Claret 1995; Claret & Gimenez 1995) with metallicity ($X = 0.73$, $Z = 0.01$), ($X = 0.70$, $Z = 0.02$) and ($X = 0.75$, $Z = 0.03$). We found that $\log \mathrm{age} < 8.65$, with age in yr, for HD 209253, which is in good agreement with the age obtained by Spangler et al. (2001). For HD 151044, the age we found is some 4 times larger than that quoted by Spangler et al. (2001).

Silverstone (2000).—This sample includes four subsamples. (1) The initial focus was on an unbiased survey of nearby stars, with care taken to span the stellar parameters of mass, age, and multiplicity. The targets were selected from the Gliese catalog (a distance-limited catalog of stars closer than 25 pc). The distance limit was chosen such that the expected range of fractional luminosity, scaled to the apparent brightness of the targets, would be brighter than the anticipated *ISO* detection limits. Spectral types of the main-sequence targets were chosen to span the mass range of about 0.5 to 2 $M_\odot$. They preferred stars whose ages were known in the literature. (2) In addition to this distance-limited survey, a selection of stars with indication of youth ($\log \mathrm{age} \sim 8.5$), but whose distances placed them beyond the distance cutoff described above, was added. (3) Because *ISO* turned out not to be as sensitive as anticipated, midway through the project the unbiased survey was abandoned in favor of observations of Vega phenomenon candidates with good *IRAS* 60 μm measurement but generally only upper limits at 100 μm. These targets were selected from the *IRAS* Faint Star Catalog (FSC) file and the SAO catalog. (4) Finally, a selection was made consisting of 23 stars from the Bright Star Catalog and with spectral types from A to G, located on the main sequence and occurring in the region of the sky missed by the *IRAS* all-sky survey.

Silverstone (2000) estimated ages from the Ca II H and K line strengths. We have redetermined the ages for the stars with a 2 σ excess detection and for which the age, as calculated by Silverstone (2000), is higher than 10 Myr. From a literature study, we found that HD 25457 is a member of the Local Association (Montes et al. 2001) and that HD 164249 belongs to the β Pictoris moving group (Zuckerman et al. 2001). HD 4614 and HD 131156 are components of nearby visual binary stars, which when put on isochrones, were found to have ages of 4 ± 2 and 2 ± 2 Gyr respectively (Fernandes et al. 1998). For the remaining stars with a spectral type between B9 and G5, we have checked the age using the isochrones of Claret (Claret 1995; Claret & Gimenez 1995) with metallicity ($X = 0.73$, $Z = 0.01$), ($X = 0.70$, $Z = 0.02$), and ($X = 0.75$, $Z = 0.03$). The ages obtained by this method give, on average, an age 0.39 dex larger in $\log t$ (where t is given in yr), which we consider to be within the errors of the different age determination methods. For two objects no independent age estimate could be made, namely, the K star HD 165341 and the F star HD 38207, for which no accurate parallax is available.

The star HD 35850 deserves extra attention: it is the only young star of the whole sample with relatively low fractional luminosity. The young age of this star appears rather secure: not only does it belong to the β Pictoris moving group, but also the high lithium content and the high X-ray flux definitely point toward a genuine youth for this star (Wichmann, Schmitt, & Hubrig 2003). On the other hand, we feel that the identification of this star as a Vega-type object may need confirmation. Looking in detail to the ISOPHOT mini-map, the observations show (in contrast to the maps of other Vega-excess stars), for only half of the pixels, the highest flux when centered on the star. The

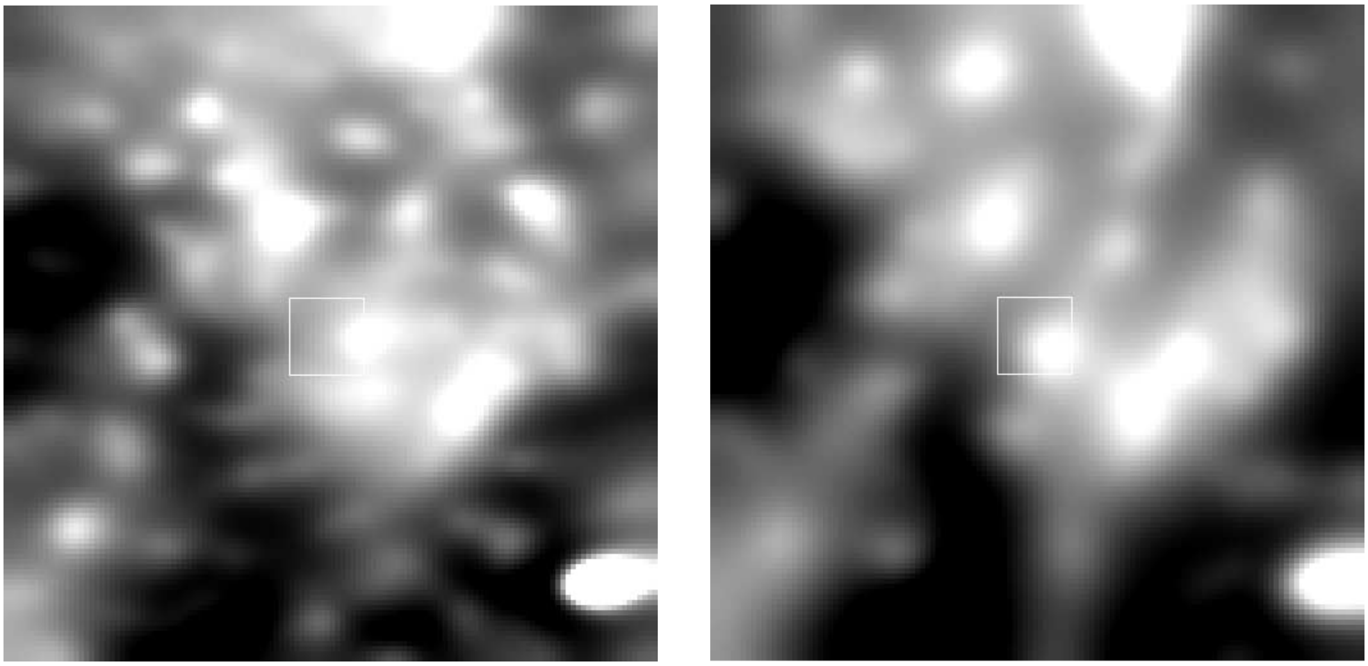

FIG. 1.—HIRAS maps of the region around HD 35850 at, respectively, 60 μm (*left*) and 100 μm (*right*). The size of each map is $30' \times 30'$. The rectangle in the middle of each map is an indication of the total size of the region measured by the ISOPHOT C100 raster.

HIRAS maps at 60 and 100 μm of the region around HD 35850 (Fig. 1) show an area of extended cirrus with lot of structure and different equally bright points. The rectangle, plotted in the middle of these maps, is an indication of the size of the region seen by the ISOPHOT mini-map (not on the true position because of the small mispointing of *ISO* and *IRAS*). From inspection of these HIRAS maps, the possibility arises that the IR excess of HD 35850 is related to the star being located in a zone of extended cirrus.

The K giant HD 3627 (G. *Decin et al.* 2004*, in preparation*).—HD 3627 has a strong IR excess at 60 and 90 μm and is an ISOPHOT C100 point source (G. Decin et al. 2004, in preparation). The excess is most probably due to a debris disk and not to cirrus or an extended source. HD 3627 is, at the moment, the only known ISOPHOT C100 point-source K giant and is most probably the successor of an F-type main-sequence star. All K giants with IR excess from the list of G. Decin et al. (2004, in preparation) and Kim, Zuckerman, & Silverstone (2001) are rejected as debris-disk stars because of the fact that the IR excess is extended.

The parameters for all stars are listed in Table 1. The first column gives the name of the stellar target. Columns (2), (3), and (5) tabulate, respectively, the V magnitude, the $B-V$ color, and the spectral type as listed by SIMBAD. The parallax, as measured by *Hipparcos*, can be found in column (4). The logarithm of the *published* age as determined by the different mentioned authors is given in the column (6), while column (7) gives the fractional luminosity as we determined it. Column (8) contains the *revised* ages as obtained by the above mentioned strategy, and the references for these ages are tabulated in column (9). In the last column the relative *reliability* of the revised age determination is indicated on the basis of the following criteria: 4, sure age because star is member of a cluster or moving group; 3, object is a member of a binary system for which both components fit on the same isochrone; 2, age of the field star could be determined by two methods (isochrones and chromospheric activity) with a maximal difference of 0.40 dex in log age (uncertainty for isochrone-fitting is $\sim$0.40 dex and for chromospheric activity $\sim$0.2 dex [Lachaume et al. 1999]); 1, large uncertainty on the age because the age could only be determined using one method, or two methods give an age difference of more than 0.40 dex in log age. The only exception to these criteria is HD 35850. While the age determination of this star is secure, it is questionable whether the IR excess tentatively detected by ISOPHOT is connected to the source. For this reason, the relative reliability of this star is reduced to 1.

3. RELATIONSHIP BETWEEN LIFETIME AND FRACTIONAL LUMINOSITY

The results listed in Table 1 are illustrated in Figure 2. In Figure 2*a* the fractional luminosity is plotted as a function of the *published* age for all samples mentioned above. In Figure 2*b*, the same data is plotted, but now over the *revised* ages as described in the current paper. Figures 2*a* and 2*b* also show the power law found by Spangler et al. (2001). Figure 2*c* repeats the same data, but now the symbol sizes reflect the age weight: large symbols show relatively secure ages, small symbols correspond to large error bars. Finally, in Figure 2*d* the sample is increased by adding a check-up *IRAS* sample obtained from Song et al. (2000, 2001). These data have not been reevaluated as to the accuracy of their age and fractional luminosity, but they seem to follow the overall distribution of points derived from *ISO* observations quite well.

For the following discussion, we mainly refer to Figure 2*b*, which contains fractional luminosity as obtained by *ISO* data versus the revised ages. The distribution of points in this diagram has a number of features:

1. There appears to be a clear cutoff at about $f_d \approx 10^{-3}$. The sample contains no Vega-like stars with significantly higher f_d -values.

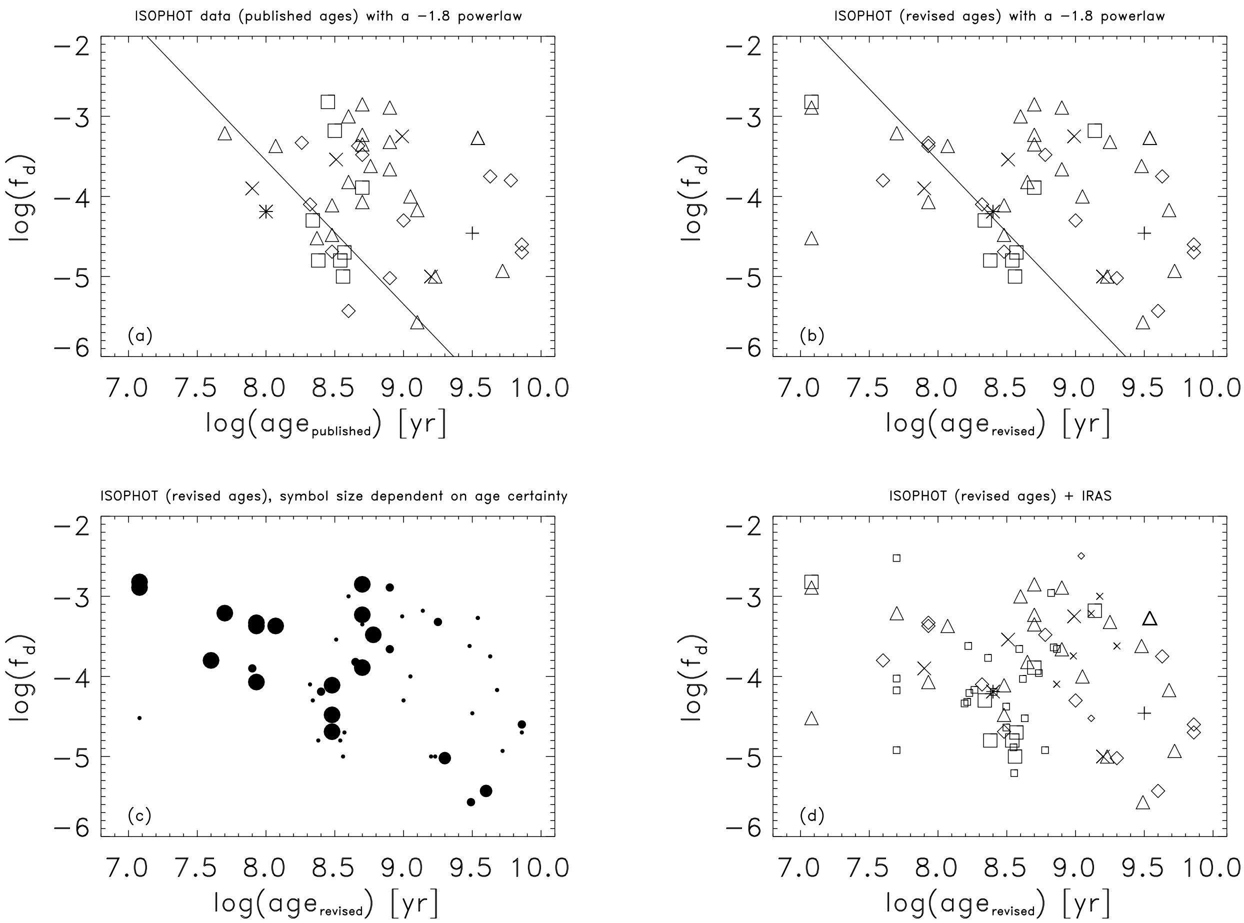

FIG. 2.—Fractional luminosity of the IR excess as a function of age. (*a*) Data obtained by the different groups using the ISOPHOT C100 camera (Decin et al. 2000; Habing et al. 2001; Silverstone 2000; Spangler et al. 2001). *Squares*: A main-sequence stars. *Triangles*: F main-sequence stars. *Diamonds*: G dwarfs. *crosses*: K dwarfs. *Plus signs*: K giant HD 3627 (Decin et al. 2004, in preparation). (*b*) *Revised* age (see text) vs. the fractional luminosity. (*a*) and (*b*) are overplotted with the regression line obtained by Spangler et al. (2001) with slope −1.76. (*c*) Same as (*b*), but the relative symbol size depends on the reliability of the age determination (see text). (*d*) Same as (*b*), but the sample is increased by the *IRAS* sample from Song et al. (2000, 2001) (*small symbols*) to check the ISOPHOT data.

2. The same upper cutoff of $f_d \approx 10^{-3}$ is valid throughout the diagram, and seems to be reached both by young and old stars. In particular, there are several cluster stars with well-determined ages between 300 and 700 Myr that do have high f_d-values, far away from the power law as determined by Spangler et al. (2001).

3. The lower-left corner of the diagram is almost empty, which means there are few young stars with small Vega-like excesses in the sample. The only example in the current sample is HD 35850, which, as we have discussed above, might possibly be the result of cirrus confusion. With some optimism, one might see a cutoff line with a slope of approximately −1.3, touching to the lowest f_d values in each age bin.

4. The lower cutoff for f_d is about 10^{-5}; there are very few stars below this line.

4. DISCUSSION

The different properties for the observed distribution in the age-f_d diagram, as mentioned above, need a thorough discussion of their reliability and significance.

4.1. *The Upper Cutoff: A True Limit*

The first important feature of the observed distribution of stars is the upper cutoff. The conclusion can hardly be escaped that old stars with fairly high fractional excesses do exist. Though it is admittedly difficult to obtain precise ages for individual stars, it is highly unlikely that the fact that the upper right part of the figure is densely populated is due to uncertainties on the ages.

Apparently, there are no stars that physically could be described as Vega-like stars (following the definition of Lagrange, Backman, & Artymowicz 2000) with fractional luminosities above this limit. This result appears to be robust in the sense that it cannot be ascribed to a selection effect. If Vega-type stars with larger fractional luminosities exist, it is most unlikely that *IRAS* would not have detected any of them. The absence of large excesses must have a physical reason. We address this issue in Paper II.

4.2. *The Lower Cutoff: The Sensitivity Limit*

The lower cutoff in the diagram around $f_d \approx 10^{-5}$ is simply the sensitivity limit of the current measurements. The radiation of smaller amounts of dust is no longer stronger than the luminosity of the star at 60 μm, and the dust emission cannot be detected with significance. Since the dust emission of Vega-like stars is detected by measuring the difference between the observed 60 μm flux and the predicted photospheric flux, this limit is set by two important factors: the absolute calibration of the IR photometer and the accuracy by which we know the photospheric flux. Therefore, the increased *sensitivity* of *SIRTF* alone will not push down this limit significantly. A much better *absolute calibration* is necessary as well. Also, significant work on understanding the photospheres of the individual stars will be required.

4.3. *Few Young Stars with Small Amounts of Dust?*

The lower-left corner of the age-f_d diagram appears to be empty. Is this feature significant, or is it caused by a small sample size or a selection effect? Table 1 contains 10 stars younger than 200 Myr. Except for HD 35850, all those stars have excesses above the line touched to the lowest fractional luminosities in each age bin, with a slope of approximately -1.3. The data are, however, currently not good enough to make a strong statement about the correctness of the slope. We can only claim that there is a decline with a slope between -1 and -2. This result is also supported by the volume-limited sample of Habing et al. (1999, 2001). The youngest six stars in this sample *all* have a Vega-like excess. The youngest stars in this sample *without* an excess is about 200 Myr old. So, it is quite possible that stars in this age range and with lower Vega-like excesses are intrinsically rare. However, it cannot yet be excluded that their apparent scarcity is due to the small number statistics of searches for such objects in the solar neighborhood and—for stars farther out—to the low sensitivity of the observational tools used so far. *SIRTF* will certainly provide large enough samples to address this question.

4.4. *The Age-f_d Power Law*

When we want to say something about the evolution of debris disks with time, we have to stress that two effects on this relation have to be treated separately: (1) the dependence of the dust mass, or correlated f_d, on age, and (2) the evolution of the fraction of stars displaying the Vega phenomenon.

We see very little evidence for the existence of a power law describing globally the dependence of f_d on age. The errors on the determination of the age and the fractional luminosity cannot move all Vega-like stars to one single slope in the diagram. Also, the maximum amount of dust seems to be independent of age. The decline as found by Spangler et al. (2001) relies heavily on the inclusion in his sample of three very young clusters for which the infrared excesses stem from protostellar disks; when these clusters are removed, and only genuine Vega-type systems are considered, the resulting relation is much less clear. Moreover, we note that Spangler et al. (2001) also detected three fairly large excess stars. These stars are among others located in Coma Berenices, which is the second oldest cluster in their sample. These stars surely cannot be moved to the power law as found by Spangler et al. (2001).

A power law can, however, be present for individual stars. The absence of intermediate Vega-like excesses in young stars might be the strongest evidence for a time evolution of the excess in individual sources: since at ages of 200 Myr and up many stars do have intermediate f_d values, the absence of younger stars with similar excesses would mean that stars have evolved from high f_d at young ages to low f_d at 200 Myr and beyond. As we discuss in Paper II, this places interesting conditions on the structure and mass of young debris disks.

One can also expect that the fraction of stars having a debris will decrease in time because the debris disks will be lost. While clusters should be a good statistical basis to investigate the real time dependence, the incompleteness (small samples for which the photosphere is not always detectable) of the sample available today makes it difficult to address this question. Therefore, we refer to the volume-limited sample of Habing et al. (1999, 2001). In this sample, all stars younger than 200 Myr display an IR excess. The stars that are younger than 400 Myr have a 60% chance to have a debris disks, while only 9% of the stars older than 400 Myr have a Vega-like IR excess. On average, 16% of the stars from this volume-limited sample occur with an IR excess. Also, Decin et al. (2000) found five Vega-like objects in a sample of 30 G dwarfs with no bias with respect to age and the very occurrence of an IR excess. These fractions are in good agreement with the fraction of main-sequence stars displaying the Vega phenomenon as obtained by *IRAS*, namely, 13% $\pm$ 10% (Plets & Vynckier 1999).

We want however to stress that the evolution of debris disks in a cluster can differ from these around field stars because cluster dynamical interaction between stars may affect circumstellar disks in a way that is unlikely for stars in a field.

5. CONCLUSIONS

In this paper, the time dependence of debris disks is reinvestigated from IR studies obtained by ISOPHOT. Our reevaluation of these data led to some important conclusions: (1) a large spread of fractional luminosity occurs, but (2) there are few very young stars with intermediate or small IR excesses; (3) there appears to be a clear maximum for the fractional luminosity at a given age around $f_d \approx 10^{-3}$, and (4) a debris disk is more common around young stars than around old ones. However, it is clear that this field of research is eagerly awaiting the possibilities offered by the *SIRTF* satellite. The higher sensitivity of this instrument will allow more accurate measurements of statistically relevant samples in clusters and should also enable us to find out whether the scarcity of young stars with real but low excesses is genuine. To reach these goals, a good absolute calibration of the instruments and significant work on understanding the photospheres of the individual stars will be required. For studies of the Vega phenomenon in the field, it will remain important to complement *SIRTF* observations with ground-based studies that allow to constrain the stellar ages to within useful limits.

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