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SUBMILLIMETER CONSTRAINTS ON DUST NEAR LINDROOS' POST T TAURI STARS

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ABSTRACT

Young stars from the dynamical sample identified by Lindroos [A&A, 156,223 (1986)] have been observed at 800 μm wavelength using the James Clerk Maxwell Telescope on Mauna Kea. The new data are used to constrain the mass of circumstellar dust around these stars. The Lindroos sample is dominated by low-mass stars of age $(3-150)\times 10^6$ yr, intermediate in age between the T Tauri and main-sequence stars. When combined with previous measurements, the present observations are compatible with the depletion of circumstellar dust on a time scale $\tau \sim 10^{7.0}$ yr. If this dust is present in circumstellar disks, then τ represents the lifetime of these disks.

1. INTRODUCTION

Many young stars emit more infrared and submillimeter radiation than can be produced from their photospheres alone. A fraction of the T Tauri stars shows excess infrared emission at 2 and 10 μm (Strom *et al.* 1989), as well as excess emission near one millimeter wavelength (e.g., Weintraub *et al.* 1989; Adams *et al.* 1990; Beckwith *et al.* 1990). These excesses have long been attributed to thermal emission from circumstellar dust, presumably left over from the epoch of formation.

The mass of circumstellar dust can be most directly estimated from the strength of the submillimeter radiation. For example, Beckwith *et al.* (1990) infer disk masses (dust plus gas) mostly between $10^{-1}\ \mathscr{M}_\odot$ and $10^{-3}\ \mathscr{M}_\odot$ in their sample of detected T Tauri stars, and *dust* masses about two orders of magnitude smaller. While the derived masses are uncertain by at least an order of magnitude (Adams *et al.* 1990; Draine 1990), it is clear that large masses of circumstellar dust are needed to account for the observed submillimeter emission. The small visual extinction per unit dust mass measured towards T Tauri stars is incompatible with spherical dust geometries, and suggests that this material is confined within dusty circumstellar disks, rather than in more nearly spherical dust envelopes (Adams *et al.* 1987). Unfortunately, the dust disks are too small (typically ~100 AU) to be well resolved using current infrared or submillimeter technology. Instead, their properties must be inferred from models applied to broadband spectral observations.

One of the outstanding scientific questions concerns the lifetimes of the circumstellar disks surrounding young stars. Disks should grow in mass by the continued accretion of infalling matter, while numerous physical processes compete to remove material from the disks. Amongst these are included radiation drag (the "Poynting–Robertson effect"), internal viscous dissipation of orbital energy, drag forces from stellar winds and planet formation. Micron sized grains will be removed via the Poynting Robertson effect on a time scale $\sim 10^3$ yr. Internal viscosity in the disk will cause some material to spiral into the central star and, presumably, to be absorbed there. The time scale for viscous dissipation is unknown, because the magnitude of the disk viscosity is uncertain. The inner regions of disks might be eroded by high velocity stellar winds, although the time scale for this is also highly uncertain. Massive disks ($\mathscr{M}_{\rm disk} \sim \mathscr{M}_{\rm star}$) might support spiral waves which promote rapid collapse (Adams *et al.* 1989). Lastly, incorporation of dust grains into comets and planets represents another "loss" process from the disk. The time scale is again poorly constrained from theory. However, it is known that the terminal bombardment phase of our own solar system lasted for $\sim 5\times 10^8$ yr (e.g., Wetherill 1990), setting a rough upper limit to the time scale for disk depletion by planet growth. With so many processes, it is difficult to obtain meaningful theoretical estimates of the lifetimes of the dust disks around pre-main sequence stars. Instead, we must rely on observations to determine the disk lifetimes.

While the lifetimes of individual disks cannot be determined, the statistical lifetimes can be found from observations of many stars. Empirical estimates of disk lifetimes can be obtained by measuring the incidence of thermal excess among stars as a function of their age. At a wavelength $\lambda \sim 1300\ \mu$m, the excess appears undiminished in T Tauri stars as old as 10^7 yr (Beckwith *et al.*, 1990). In the thermal infrared (wavelength $\lambda \sim 10\ \mu$m), it is found that the excess disappears in stars older than about 3×10^6 yr (Strom *et al.* 1989). The difference, if significant, might reflect faster destruction of dust in the hotter, inner parts of circumstellar disks. Both time scales are very short compared to the above-mentioned ~0.5 Gyr terminal bombardment phase in our own solar system.

There are several practical problems in the determination of disk lifetimes. First, the ages of pre-main sequence stars are notoriously uncertain and model-dependent. Ages determined by fitting evolutionary tracks to stars on the HR diagram are probably not good to better than a factor of two (e.g., Mazzitelli 1989). Second, pre-main sequence stars with ages $>10^7$ yr appear to lack the distinguishing optical char-

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acteristics which are used to identify the T Tauri stars. Specifically, the prominent Hα emission and Lithium absorption lines used to identify these stars in objective prism surveys are weak or absent in the older objects. Therefore, stars older than 10^7 yr generally do not appear in catalogues of T Tauris. For this reason, it is difficult to assess the significance of the $\sim 10^7$ yr survival time for dust disks suggested by the sample of Beckwith *et al.* (perhaps it is an artifact of the absence of older known T Tauri stars?). *Do dust disks outlive the T Tauri phase in young stars?* To answer this question we must identify a set of pre-main sequence stars older than the oldest T Tauri stars.

A method to identify such stars based on membership in wide binaries with B stars was advanced by Murphy (1969). He reasoned that secondary companions to O and B stars should be coeval with their primaries, and (because O and B stars are massive and therefore young) must themselves be young (see also Gahm *et al.* 1983). Lindroos (1986) compiled a list of wide binaries in which the primary component is of type O or B. A majority of the secondaries found are of spectral types F, G, or K, and about 50% of these stars, according to Lindroos (1986), show spectral features expected of young stars. On the HR diagram, the Lindroos secondaries fall on or slightly above the main sequence. The ages of the primary stars are estimated from their positions on the HR diagram, by comparison with theoretical evolutionary tracks. The ages of some of the secondaries can be independently estimated from contraction track models. In general, Lindroos found that the primary and secondary star ages agree. Although the absolute ages of the Lindroos stars are uncertain, their location on the HR Diagram between the T Tauri stars and the main sequence suggests that the Lindroos stars are older than the former but younger than the latter. It is thus a plausible working assumption that many of the Lindroos stars are aged T Tauri and other pre-main sequence stars. The validity of this assumption is further discussed in Sec. 3.

Accordingly, we have observed a subset of the Lindroos stellar sample at 800 μm, with our principal aim being to constrain the mass of dust projected in the vicinities of these stars. The observations are described in Sec. 2 and their interpretation in Sec. 3.

2. OBSERVATIONS

Submillimeter observations were taken at the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, in November 1990 and April 1991. The JCMT is a 15 m diameter telescope operated at Nasmyth focus and capable of diffraction-limited resolution at wavelengths down to $\lambda = 350$ μm (860 GHz). The present observations were taken at $\lambda = 800$ μm (375 GHz) and 1100 μm (270 GHz) using the facility bolometer UKT14 (Duncan *et al.* 1990). All observations employed a 65 mm diameter focal-plane diaphragm, which subtended 16.5″ at 800 μm and 18.5″ at 1100 μm, measured in the plane of the sky (the diffraction-limited resolutions at these wavelengths are 13.5″ and 18.5″). The diaphragm was chopped to a point distant 40″ in azimuth for background subtraction, at a frequency 7.8 Hz. In addition, the telescope was periodically nodded 40″ in azimuth so as to remove possible asymmetries between the object and sky beams.

The pointing of the JCMT was verified to be accurate at the $< \pm 2''$ level by repeated measurements of submillimeter sources having accurately known positions. Photometric calibration was obtained from repeated observations of Mars, CRL 618, IRC+10°216, and secondary standards (Sandell 1992). The statistical characteristics of the submillimeter data dictated the method of observation. Integrations were taken as a series of object–sky "pairs," each of 10 s duration. Sky noise is not randomly distributed among the pairs, so that increasing the number of pairs beyond about 15–20 per integration does not improve the signal to noise ratio. Therefore, we observed using a series of 15–20 pairs of integrations of 10 s each, and took the weighted mean of the results as the best estimate of the true value. Variability in the opacity and stability of the submillimeter sky made it impossible to reach a fixed sensitivity limit for each source. The JCMT/UKT14 is most sensitive to thermal continuum sources at $\lambda = 800$ μm. Nevertheless, on atmospherically poor nights, we were forced to observe instead at 1100 μm. The 1100 μm observations are summarized in this paper for completeness, but are less physically constraining than the 800 μm data, and are not used in the subsequent analysis.

The Lindroos stars were selected from Table 1 of Lindroos (1986) according to two criteria. First, the heliocentric distance was required (with one exception) to be $\Delta \leqslant 250$ pc, in order to minimize geometrical dimming of the sought-after submillimeter radiation according to the inverse square law. Second, the declination of the stars was required to be $\delta \geqslant -50°$. Angular offsets of the secondary stars from their primaries were obtained from Jeffers *et al.* (1963). As a control of the Lindroos sample, we also observed T Tauri stars from the Taurus–Auriga region. The T Tauri stars were selected in numerical order from those in Table 1 of Beckwith *et al.* (1990). Some stars listed in Table 2 were independently observed by Weintraub *et al.* (1989) and Adams *et al.* (1990). In all cases, the present observations give flux densities consistent with those previously published.

The relative youth of *some* of Lindroos' dynamically identified stars has apparently been confirmed by the detection of large photospheric Lithium abundances (Martin *et al.* 1992; Pallavicini *et al.* 1992). Eight of a subset of 14 Lindroos stars have been shown to have radial velocities and metallicities consistent with physical association with the hot primaries (Martin *et al.* 1992), while $\leqslant 40\%$ of 37 stars show spectral characteristics indicative of youth (Pallavicini *et al.* 1992). Among the stars in Table 1, Pallavicini *et al.* classified HD 17543, HD 27638, HD 33802, HD 90972, HD 108767, and HD 127304 as "certain or possible physical systems" and HD 8803, HD 23793, HD 35007 as "likely optical systems." The remainder of the stars in Table 1 were not observed by these authors. Evidently, the selection method employed by Lindroos is imperfect, but it does detect a significant fraction of young stars that might have escaped notice by any other means.

Submillimeter observations of the Lindroos stars are summarized in Table 1 and of the T Tauri stars in Table 2.

TABLE 1. Observations of Lindroos stars.

N (1)	Name (2)	Δ [pc] (3)	log(Age) (4)	Sp (5)	S_{800} (6)	S_{1100} (7)	S^*_{800} (8)	S^*_{1100} (9)	log M_d (10)
1	HD1438	171	8.0	F3V	≤51	--	≤76	--	≤-4.39
2	HD8803	164	8.2	F6VP	≤54	--	≤74	--	≤-4.40
3	HD17543A	157	7.8	F8V	≤57	--	≤72	--	≤-4.42
4	HD17543B	157	7.8	F8V	≤39	--	≤49	--	≤-4.58
5	HD23793	131	<7.5	F3Vp	≤27	--	≤24	--	≤-4.89
6	HD27638	79	8.1	G2V	≤96	≤33	≤31	≤11	≤-4.78
7	HD33802	75	7.6	G8VE	≤75	≤36	≤22	≤10	≤-4.93
8	HD34798	216	<7.3	B6V	--	≤33	--	≤79	--
9	HD35007	236	7.4	G3V	--	≤87	--	≤247	--
10	HD36960	528	6.6	B1V	35±11	--	498±156	--	-3.57±0.12
11	HD74067	69	7.8	A2V	≤57	≤36	≤14	≤9	≤-5.13
12	HD90972	99	8.1	F9VE	≤81	≤42	≤41	≤21	≤-4.66
13	HD112413	29	7.4	F0V	≤42	≤52	≤1.8	≤2.2	≤-6.02
14	HD108767	23	8.0	K2VE	≤42	≤39	≤1.1	≤1.1	≤-6.23
15	HD127304	91	7.9	K1V	≤42	--	≤18	--	≤-5.02
16	HD61555A	127	7.1	B7V	≤45	≤30	≤37	≤25	≤-4.70
17	HD61555B	127	7.1	B7V	≤57	≤33	≤47	≤27	≤-4.60

Notes

(3), (4)	Heliocentric Distance [pc] and log Age [years], from Lindroos 1986.
(5)	Spectral Type of the secondary, from Lindroos 1986.
(6), (7)	Flux densities measured at 800 μm and 1100 μm, respectively.
(8), (9)	Corresponding flux densities scaled to distance 140 pc.
(10)	3σ limiting dust mass [solar masses] from Eq. (2).

3. DISCUSSION

To compare the observations of the Lindroos stars with the T Tauri stars, we scaled all measurements to the heliocentric distance of Taurus (taken to be 140 pc) using $S_\nu^* = S_{\rm obs}(\Delta/140)^2$. Here, $S_{\rm obs}$ (mJy) is the observed flux density, and Δ (pc) is the heliocentric distance of the Lindroos star. The scaled flux densities, S_ν^*, are listed in columns (8) and (9) of Table 1. Figure 1 shows the scaled flux densities of the Lindroos and T Tauri stars as functions of the estimated stellar ages (Lindroos 1986; Beckwith *et al.* 1990). In the figure, horizontal bars signify factor of 2 uncertainties in the stellar ages, while 3σ upper limit flux densities are indicated by vertical arrows.

TABLE 2. Observations of T Tauri stars.

N (1)	Name (2)	Other Name (3)	Δ [pc] (4)	log(Age) (5)	Sp (6)	S_{800} [mJy] (7)	log M_d (8)
1	HBC 23	FM Tau	140	6.32	M0	≤57	≤-4.51
2	HBC 24	FN Tau	140	4.86	M5	≤75	≤-4.39
3	HBC 25	CW Tau	140	6.28	K3	209±43	-3.95±0.08
4	HBC 26	FP Tau	140	5.53	M5.5	≤243	≤3.88
5	HBC 27	CX Tau	140	5.95	M2	≤96	≤-4.29
6	HBC 28	CY Tau	140	5.87	M1	198±29	-3.97±0.06
7	HBC 29	V410 Tau	140	5.43	K7	≤147	≤-4.11
8	HBC 30	DD Tau	140	5.54	M1	≤60	≤-4.49
9	HBC 31	CZ Tau	140	6.13	M1.5	≤60	≤-4.49
10	HBC 32	BP Tau	140	5.85	K7	126±29	-4.17±0.11
11	HBC 33	DE Tau	140	5.40	M1	≤81	≤-4.36
12	HBC 34	RY Tau	140	5.33	K1	543±52	-3.54±0.10
13	HBC 35	T Tau	140	5.27	K1	860±80	-3.34±0.05
14	HBC 36	DF Tau	140	5.00	M0.5	≤78	≤-4.38
15	HBC 38	DH Tau	140	6.04	M0	66±22	-4.45±0.15
16	HBC 39	DI Tau	140	5.97	M0	≤72	≤-4.42
17	HBC 41	IQ Tau	140	5.79	M0.5	172±35	-4.04±0.08

Notes

(4), (5)	Heliocentric Distance [pc] and log Age [years], from Beckwith *et al.* (1990).
(6)	Spectral Type, from Beckwith *et al.* (1990).
(7)	Flux density measured at 800 μm.
(8)	Dust mass [$M_{\rm sun}$] from Eq. (2).

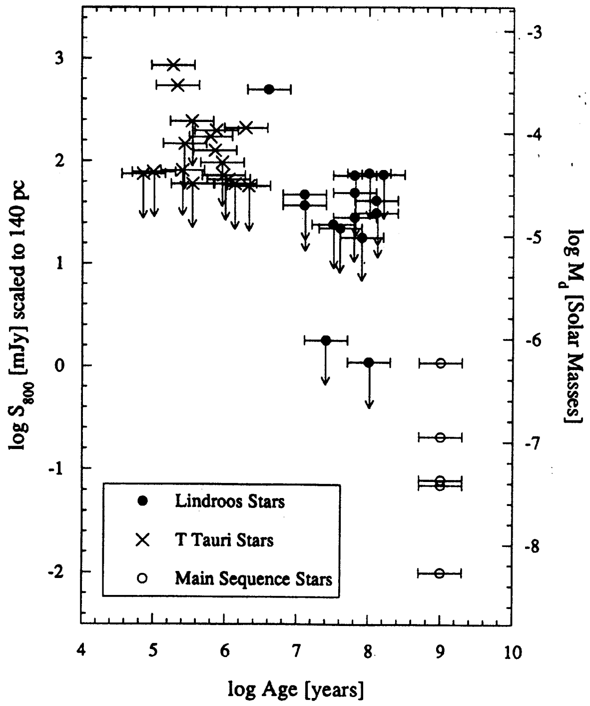

FIG. 1. Scaled 800 μm flux density versus the logarithm of the stellar age, for Lindroos' and T Tauri stars observed with the JCMT. Scaled 800 μm flux densities for main sequence stars observed by Becklin & Zuckerman (1990) are added for comparison. Arrows indicate that the measurement is a 3σ upper limit to the 800 μm flux density. Horizontal bars denote factor of two uncertainty in the age. The right hand ordinate shows the approximate dust mass derived from the scaled flux density using Eq. (2). The figure shows that β Pic type dust clouds could surround the Lindroos stars and yet remain undetected.

From Fig. 1 and Table 1, it may be seen that only one Lindroos star (HD 36960) was positively detected. Perhaps not coincidentally, HD 36960 is the youngest of the observed Lindroos stars, at age $t=3\times10^6$ yr. It also has the highest luminosity and presumably has a high mass. When scaled to 140 pc, HD 36960 is comparable in flux density to the brighter T Tauri stars, implying that it is surrounded by a substantial mass of dust. The remaining Lindroos stars were not detected.

It is of interest to estimate the limiting dust masses implied by our 800 μm photometry. Accurate masses cannot be obtained, since in most cases we possess no significant constraint on the infrared–submillimeter spectral energy distribution (c.f. Adams *et al.* 1987). However, crude masses can be estimated as follows. The flux density produced by dust of

1994AJ....108..661J

total mass $\mathcal{M}_d$ at uniform temperature T_d, when observed at frequency ν from distance Δ, is

$$S_\nu = B_\nu(\bar{T}_d)\,\frac{\kappa_\nu \mathcal{M}_d}{\Delta^2}\,. \tag{1}$$

Therefore, the mass may be written

$$\mathcal{M}_d = \frac{\Delta^2 S_\nu}{B_\nu(\bar{T}_d)\kappa_\nu}\,. \tag{2}$$

The effective dust opacity, $\kappa_\nu(\mathrm{m}^2\,\mathrm{kg}^{-1})$ is uncertain (cf. Hildebrand 1983; Wright 1987; Draine 1990); we adopt $\kappa_\nu(\lambda=800\ \mu\mathrm{m})\sim 0.17\ \mathrm{m}^2\,\mathrm{kg}^{-1}$ to be compatible with Zuckerman & Becklin (1993) and note that both this value and the masses derived from Eq. (2) are uncertain by factors of several. In principle, the opacity could be smaller (and the dust masses larger) if the grains are compact and have grown by agglomeration to sizes much larger than a wavelength. The effective mean dust temperature is taken as $\bar{T}_d=30$ K. This temperature is representative of the disks inferred around T Tauri stars by Beckwith *et al.* (1990). The temperature itself is uncertain, but for purposes of comparison, the assumed value is adequate.

With the above parameters substituted in Eq. (2), 1 Jy at 800 μm and 140 pc corresponds to a dust mass $\sim 5.4\times 10^{-4}\ \mathcal{M}_\odot$. The derived limiting masses are listed for the Lindroos and T Tauri stars in Tables 1 and 2. There it may be seen that the limiting dust masses are $<10^{-4}$ to $10^{-6}\ \mathcal{M}_\odot$, depending mainly on the distance to the star, Δ.

Figure 1 shows that the detected stars all have ages $\leqslant 10^{6.5}$ yr. To what physical process does this time scale correspond? We consider it likely that we have measured the time scale for agglomerative growth of the grains in the circumstellar disk. Growth of the grains decreases the effective grain opacity, κ_ν, and so decreases the emitted intensity per unit mass. For macroscopic spheres, the cross section per unit mass varies inversely with the grain size, so that an increase in the mean particle size by a factor of 10 corresponds to a decrease in κ_ν of the same order. For small particles, or particles with nonspheroidal shape, the effect of a change in size is less simple. Nevertheless, it is still likely that growth of the mean particle size by a factor of a few would lead to a decrease in the emitted intensity by a factor of a few.

Grain agglomeration is of course a necessary precursor to planetesimal and planet growth, but sets only a lower limit to the time scale for the growth of planets around solar mass stars. Thus, it is perhaps not surprising that the measured time scale is an order of magnitude shorter than the time estimated for the formation of the meteorites in our own solar system and shorter than the $\sim 5\times 10^8$ yr terminal bombardment phase of the solar system (Jewitt 1991).

The Lindroos stars (by their method of selection) are binaries, and it is reasonable to enquire whether the gravity of the primary could have influenced the disk structure or disk lifetime in the secondary (Mathieu 1992). Two observations seem relevant to this question. First, the Lindroos stars are *wide* binaries: the median separation of the observed stars in the plane of the sky is 1600 AU. This separation is large compared to the typical 100 AU size scale of disks (Beckwith *et al.* 1990; Adams *et al.* 1990; Weintraub *et al.* 1989). Second, many of the T Tauri stars which exhibit thermal excesses attributed to dust disks are also members of binary or multiple systems: perhaps 60%–70% of T Tauri stars are multiple (Simon *et al.* 1992; Ghez *et al.* 1993; Leinert *et al.* 1993; Reipurth & Zinnecker 1993). The fraction of T Tauri stars showing submillimeter excess is not statistically different between single and multiple stars, suggesting that the disks are not strongly inhibited by binary star membership (Beckwith *et al.* 1990).

The absence of thermal emission from dust near Lindroos stars is mirrored in other observations. Tsikoudi (1990) failed to detect the Lindroos stars in 12 μm *IRAS* data. Recently, Gahm *et al.* (1994) reported 1300 μm photometry of Lindroos stars in a program of observations similar to the present one, but directed more towards objects in the southern hemisphere. None of the 16 additional stars in their paper was detected at sensitivity limits that (when scaled to 800 μm) are comparable to those in Tables 1 and 2. The low rate of submillimeter detection of Lindroos stars (1 detection among 33 stars) stands in marked contrast to the 7 out of 17 T Tauri stars detected at the same level of sensitivity (Table 2), and suggests a marked difference in dust mass between these two classes of star. In addition, Skrutskie *et al.* (1990) placed upper limits on the total circumstellar mass around stars in the Ursa Major stream (age $\sim 3\times 10^8$ yr) of order $10^{-5}\ \mathcal{M}_\odot$. These independent observations are compatible with the substantial depletion of circumstellar dust disks on time scales $\sim 10^7$ yr.

The present observational limits on 800 μm emission from Lindroos' stars by no means exclude the possibility that some or all of these stars are β Pic type dust systems. For instance, if β Pic were moved from its present distance (16.6 pc) to the distance of Taurus (140 pc), the 800 μm emission from its dust would be diminished from 80±14 mJy (Becklin & Zuckerman 1990; Zuckerman & Becklin 1993) to 1.1±0.2 mJy, and would go undetected. This is shown graphically in Fig. 1, where we have plotted the 800 μm photometry of several main sequence stars (Becklin & Zuckerman 1990; Zuckerman & Becklin 1993), scaled to $\Delta=140$ pc using the inverse square law. Figure 1 provides an observational comparison of the dust emission among a variety of stellar objects of different ages, but should not be taken to suggest any specific physical connection between the T Tauri, Lindroos, and main sequence stars. In fact, whereas the T Tauri stars exhibit "primordial" disks left over from the formation process, the β Pic dust is thought to be continually replenished by a population of comets. However, the figure does show that the scaled limiting flux densities from Lindroos stars are, with two exceptions, an order of magnitude greater than the scaled flux densities of the detected main-sequence stars. The two exceptions (HD 108767 and HD 112413) are simply the closest of the observed Lindroos stars for which we have the most sensitive limits on the presence of dust. Thus, β Pic type dust clouds around Lindroos stars would escape detection in existing data.

4. CONCLUSIONS

(1) Nearby members of Lindroos (1986) catalog of pre-main sequence stars have been observed at 800 μm using the James Clerk Maxwell Telescope. Only 1 of 17 Lindroos stars was detected at $\lambda=800$ μm wavelength with the JCMT. In addition, none of 16 additional Lindroos objects observed at 1300 μm by Gahm *et al.* (1994) were detected to similar limiting sensitivity. These low detection rates contrast with 7 detected out of 17 observed true T Tauri stars, scaled to the same photometric sensitivity.

(2) The new observations are compatible with a dramatic (>factor of 10) decline in the circumstellar dust mass at stellar ages $\sim 10^7$ yr.

(3) β Pic type dust disks would have escaped submillimeter detection around all but two of the observed Lindroos stars, owing to the low mass ($<10^{-6}\,\mathscr{M}_\odot$) in such disks.

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