Mon. Not. R. Astron. Soc. **327,** 133–140 (2001)

SCUBA photometry of candidate Vega-like sources

R. J. Sylvester, S. K. Dunkin★† and M. J. Barlow

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT

Accepted 2001 May 21. Received 2001 May 21; in original form 2001 March 8

ABSTRACT

New SCUBA measurements at millimetre wavelengths are presented for a sample of Vega-like stars. Six stars were detected, while sensitive upper limits were obtained for a further 11 sources. Most of the sample selected from a recent catalogue of Vega-like stars have infrared excesses similar to those of the prototype Vega-like stars α Lyr and α PsA. Their IR–submm spectral indices are steep, indicating that the submm emission from the discs is dominated by grains which are smaller than the wavelength of observation and that only small grains exist in those dusty discs. HD 98800 has an IR–submillimetre spectral index of less than two, which suggests that grains have grown to more than 0.3 mm in size. *Hipparcos* parallax data for HD 42137 and HD 123160 suggest that these two stars are giants rather than dwarfs, similar to the situation previously found for HD 233517. Dust masses, or upper limits, were derived for the sample; these indicate that most of the sources do not have as much dust as Herbig Ae/Be or T Tauri stars, but are likely to have dust masses comparable to those of the prototype Vega-like stars.

Key words: circumstellar matter – infrared: stars.

1 INTRODUCTION

Vega-like stars are main-sequence stars with excess emission at infrared wavelengths. During a calibration scan of the photometric standard star α Lyr (Vega), the *Infrared Astronomical Satellite* (*IRAS*) found that the flux densities at 25, 60 and 100 μm were in excess of those expected from a blackbody at the temperature of the star (Aumann et al. 1984). During the course of the mission three other bright main-sequence stars were found to exhibit this infrared (IR) excess: α PsA (Fomalhaut), ϵ Eri and β Pic which, together with Vega, have become known as the prototypes of the 'Vega-like' phenomenon. The excess emission from these main sequence stars has been attributed to circumstellar material in the form of a disc or ring. Coronagraphic and infrared imaging of β Pic (e.g. Smith & Terrile 1984, Lagage & Pantin 1994) and submillimetre imaging of all four prototype Vega-like stars (Holland et al. 1998; Greaves et al. 1998); have confirmed that the dust is indeed located in discs or tori, and shown that significant clumps of dust can exist in the discs.

We have published observations and radiative transfer models of a sample of Vega-like stars taken from the Walker & Wolstencroft (1988) catalogue (Sylvester et al. 1996, hereafter Paper I; Sylvester, Barlow & Skinner 1997). Many new candidate Vega-like systems have recently been identified by Mannings & Barlow (1998, henceforth MB98) using the *IRAS* Faint Source Survey catalogue. We have observed 12 of these sources using SCUBA, in order to measure the emission from the larger and/or cooler grains in the discs.

2 OBSERVATIONS

The observations were made using the SCUBA bolometer system in its photometric mode at the James Clerk Maxwell telescope (Holland et al. 1999). Table 1 lists the stars observed, the dates and wavelengths of the observations, and the measured fluxes. The instrumental beamsize was 14, 22 and 34 arcsec at 850, 1350 and 2000 μm, respectively. The 1997 August and December data were obtained as part of the SCUBA2 service programme, while the 1998 observations were made partly in flexibly-scheduled mode, and partly by 'normal' scheduling. We typically integrated for 1 hour per source, obtaining 1350-μm flux uncertainties of ~ 1 mJy, consistent with the published NEFD estimates for SCUBA. As well as the MB98 stars, we also observed a number of sources from our previous sample (Paper I), to improve on observations made with the old UKT14 bolometer system. One of these stars, HD 233517 (SAO 26804), was found to show extended 10-μm emission by Skinner et al. (1995), who modelled the star as being nearby and on the main sequence. Subsequently, Fekel et al. 1996) classified the optical spectrum of HD 233517 as K2 III, and presented arguments indicating that it is likely to be a first ascent giant at a distance of several hundred pc. In any case, HD 233517 is an interesting object, and was retained in our SCUBA target list.

★E-mail: s.k.dunkin@rl.ac.uk

†Present address: Space Science & Technology Department, Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX.

Table 1. New SCUBA measurements of Vega-like stars.

HD	SAO	Date	Wavelength (μm)	Flux (mJy)
34700	112630	Aug 97	1350	13.1 ± 3.1
…	…	Feb 98	1350	11.4 ± 1.2
39944	171003	Feb 98	850	8.2 ± 10.1
…	…	Feb 98	1350	3.7 ± 0.9
42137	196509	Feb 98	1350	0.2 ± 1.6
43954	151337	Feb 98	1350	1.5 ± 1.8
43955	151334	Feb 98	1350	1.1 ± 1.0
56192	218555	Feb 98	1350	3.4 ± 4.1
98800	179815	Dec 97	1350	36.8 ± 4.2
…	…	Dec 97	2000	24.8 ± 3.4
110058	223581	Feb 98	1350	0.8 ± 1.5
121617	224570	Feb 98	1350	1.0 ± 1.1
123160	158350	Feb 98	850	13.0 ± 4.3
…	…	Dec 97	1350	2.8 ± 1.2
…	…	Feb 98	1350	4.7 ± 0.9
…	…	Dec 97	2000	3.3 ± 3.1
131885	183025	Feb 98	1350	-0.2 ± 1.1
141569	140789	Feb 98	1350	5.3 ± 1.1
…	…	May 98	1350	5.6 ± 2.1
145263	184196	Feb 98	1350	0.9 ± 1.1
176638	229461	May 98	1350	4.6 ± 3.3
233517	26804	Dec 97	1350	2.5 ± 1.9
…	…	Feb 98	1350	2.7 ± 1.2

3 RESULTS

Table 2 shows the final results for the stars in our sample. Where more than one observation was taken of a single source, the figure quoted represents a weighted mean of the fluxes.

It has been found that the *IRAS* flux of one of the MB98 stars in our sample might not be associated with the optical main-sequence star. Sylvester & Mannings (2000) showed that there is a significant offset (22 arcsec) between the *Tycho* optical position of HD 39944 and the *IRAS* source position. The ESO Schmidt plates (Lauberts 1982) show a background object, ESO 488-41, which lies closer to the *IRAS* position (separation ≈14 arcsec) than does the HD star, and which could be responsible for the observed IR emission. We did detect 1.35-mm emission at the position of HD 39944. ESO 488-41 is a group of two or three interacting galaxies (Lauberts 1982). Such systems are often dusty and emit strongly in the mid- and far-IR (see e.g. Bushouse, Telesco & Werner 1998), and so it seems possible that the submm flux that we observed is in fact extragalactic in origin. On the Digitized Sky Survey image, ESO 488-41 extends to within 21 arcsec of the optical position of HD 39944, which was the position used for our observations. The 1.35-mm SCUBA beam has a FWHM of around 22 arcsec, and should thus have had a rather low sensitivity with emission from the optically-visible regions of ESO 488-41. Possible explanations include (i) the galaxy is bright in the mm, and so is detected even on the edge of the SCUBA beam; (ii) the dust emission is more extended than the visible light shown in the Sky Survey image; (iii) the mm-wave emission is in fact associated with the HD star. Mid-IR and submm imaging would be useful to determine which object is responsible for the emission. As the IR and mm-wave flux may not be due to its own circumstellar emission, HD 39944 is not included in Fig. 1.

Many of the stars in our sample have not been observed previously at millimetre wavelengths. For most of the MB98 sample we were able to obtain only upper limits to the flux. The exception to this is HD 39944, although, as mentioned above, it transpires that the IR excess associated with this star may well originate from a background galaxy. Of the stars taken from Paper I, HD 123160 and HD 141569 had not previously been detected by us at millimetre wavelengths, We now have good detections for both of these stars at 1350 μm, with fluxes that are consistent with the upper limits we obtained previously. HD 141569 has been observed previously by Walker & Butner (1995); our flux is consistent with theirs within the uncertainties of both observations. Our new flux for HD 98800 is substantially higher than our previous measurement obtained using UKT14. However, it is consistent with the CSO observations of Walker & Butner (1995). We have also obtained a measurement at 2.0 mm for this star. The flux of HD 34700 from our SCUBA measurements is lower than the published value by almost 50 per cent; this could be due to problems with the calibration of the published IRAM observations (Walker & Butner 1995). The weighted mean of our two observation of HD 233517 is 2.6 ± 1.0 mJy; for consistency with the other sources without good detections, we have adopted an upper limit of 3σ above zero, rather than above the mean, for inclusion in Table 2.

Fig. 1 plots the spectral energy distributions (SEDs) for the observed sample of stars, after dereddening using the $E(B-V)$ values given in Table 2. The stars in the MB98 sample generally have very few observations available in the literature. In several cases we were restricted to B and V or B, V, I mag from the *Hipparcos* and *Tycho* catalogues (ESA 1997), and the *IRAS* measurements from the Faint Source Catalogue (FSC; Moshir et al. 1992). Near-IR photometry for three of the MB98 sources was taken from Sylvester & Mannings (2000). For the remainder of the sample, photometric data were taken from Paper I. Intrinsic colours were taken from Schmidt-Kaler (1982). The reddenings towards the MB98 stars (see Table 2) were generally found to be small, and comparable to those found in Paper I.

Table 2 also gives the distances to the stars. Where possible, we adopted distances derived from *Hipparcos* parallax measurements; for the remaining stars, we used spectroscopic parallaxes, adopting the absolute magnitudes and intrinsic colours of Schmidt-Kaler (1982). We also used spectroscopic parallaxes for the stars with *Hipparcos* distances; comparison of the values derived from the two methods gives an idea of the accuracy of the spectroscopic parallax distances, and provides a way of checking that the stars are indeed on the main sequence (i.e. that our adopted absolute magnitudes are correct). For five of the seven stars with *Hipparcos* parallax measurements, the distances derived using the two methods were found to agree to within 0.2 dex. The spectroscopic parallax distance to HD 43955 is 180 pc, rather lower than the *Hipparcos* distance of 310^{+70}_{-50} pc. This B star is a spectroscopic binary (Abt, Gomez & Levy 1990), so the flux from the secondary star may account for part of the discrepancy in distances. More serious discrepancies exist for HD 42137 and HD 123160. The spectroscopic parallax gives a distance of 7 pc for HD 42137, while the *Hipparcos* parallax (3.17 ± 0.67 mas) implies a distance of 320^{+80}_{-60} pc. Assuming zero reddening, the latter distance gives an absolute magnitude $M_V = 0.2 \pm 0.5$, consistent with a K3 III or K4 III giant. Similarly, the spectroscopic distance for HD 123160 is 14 pc, while the *Hipparcos* parallax (-0.01 ± 1.31) gives a 3σ lower limit to the distance of 250 pc. This implies an absolute magnitude (ignoring reddening) brighter than 1.6, again consistent with a giant, rather than dwarf, luminosity classification.

To investigate further the possibility of these stars being giants, we were able to obtain spectroscopic data for HD 42137 (I. A. Crawford, private communication) and analyse luminosity-sensitive

Table 2. Derived quantities for our sample of candidate Vega-like stars (see text for details). HD 39944 is shown in parentheses because the *IRAS* source may not be associated with the HD star. $\alpha_{\rm pred}$ is the predicted 60:1350 μm spectral index obtained by fitting a Planck function to the 25- and 60-μm *IRAS* fluxes.

HD	SAO	Sp. Type	λ (μm)	Flux (mJy)	Prev. obs	Ref	$\alpha_{100:\lambda}$	$\alpha_{60:\lambda}$	$\alpha_{\rm pred}$	$L_{\rm IR}/L_*$	$E(B-V)$	dist (pc)	$M_{\rm dust}$ $\mathrm{M}_\odot$
34700	112630	G0V	1350	11.7 ± 1.1	18 ± 2	(1)	2.57 ± 0.05	2.28 ± 0.04	1.5	0.14	−0.01	90:	1.1×10^{-5}
(39944	171003	G1V	1350	3.7 ± 0.9	–	–	2.38 ± 0.10	1.79 ± 0.08	1.4		0.69	37:	6×10^{-7})
42137	196509	K3/4V	1350	<4.8	–	–	>2.1	>1.3	1.8	2.9×10^{-3}	0.54	320^{+80}_{-60}	$<6\times10^{-5}$
43954	151337	A0V	1350	<5.4	–	–	>2.1	>1.8	1.4	6.0×10^{-3}	0.02	350:	$<8\times10^{-5}$
43955	151334	B2/3V	1350	<3.0	–	–	>2.3	>1.6	1.5	4.2×10^{-5}	0.38	310^{+70}_{-50}	$<3\times10^{-5}$
56192	218555	B9/A0V	1350	<12.3	–	–	>1.9	>1.0	1.6	2.9×10^{-3}	0.25	570:	$<4\times10^{-4}$
98800	179815	K4V	1350	36.8 ± 4.2	11 ± 3	(2)	1.84 ± 0.06	1.70 ± 0.05	1.7	0.084	0.00	47^{+7}_{-6}	9.5×10^{-6}
98800	179815		2000	24.8 ± 3.4	–	–	1.73 ± 0.06	1.62 ± 0.05					
110058	223581	A0V	1350	<4.5	–	–	>2.1	>1.4	1.7	1.9×10^{-3}	0.17	100^{+11}_{-9}	$<5\times10^{-6}$
121617	224570	A1V	1350	<3.3	–	–	>2.4	>2.0	1.6	4.5×10^{-3}	0.29	120:	$<6\times10^{-6}$
123160	158350	G5V	850	13.0 ± 4.3	<4	(2)	2.42 ± 0.16	2.07 ± 0.13	1.4	4.4×10^{-3}	0.91	14†	
123160	158350		1350	4.4 ± 0.8	<16	(2)	2.65 ± 0.08	2.11 ± 0.07					3.1×10^{-7}
123160	158350		2000	<9.3	–	–	>2.1	>1.7					
131885	183025	A0V	1350	<3.3	–	–	>2.2	>1.5	1.6	8×10^{-4}	0.04	121^{+14}_{-12}	$<6\times10^{-6}$
141569	140789	A0Ve	1350	5.4 ± 1.0	9 ± 4	(1)	2.49 ± 0.08	2.23 ± 0.07	1.6	8.3×10^{-3}	0.17	99^{+9}_{-8}	$<6\times10^{-6}$
145263	184196	F0V	1350	<3.3	–	–	>2.6	>2.0	1.5	2×10^{-2}	0.16	116^{+19}_{-14}	$<5\times10^{-6}$
176638	229461	B9/A0V	1350	<9.9	–	–	>1.8	>1.1	1.7	2×10^{-4}	0.01	56 ± 3	$<4\times10^{-6}$
233517	26804	K2	1350	<3.0	–	–	>2.8	>2.5	1.6	0.057	0.49	23†	1.8×10^{-7}

References: (1) Walker & Butner (1995), (2) Sylvester et al. (1996).

Notes: the 16-mJy upper limit for HD 123160 was obtained at 1100 μm. Distances marked with a colon were estimated using spectroscopic parallax. † Spectroscopic parallax distance assuming the star is a dwarf; it may be a giant at a much larger distance. Fekel et al. suggested a distance of 600 pc for HD 233517, which gives a dust mass of $< 1.3 \times 10^{-4}\,\mathrm{M}_\odot$. The *Hipparcos* parallax for HD 123160 implies a distance > 250 pc, and hence a dust mass of $> 3 \times 10^{-5}\,\mathrm{M}_\odot$.

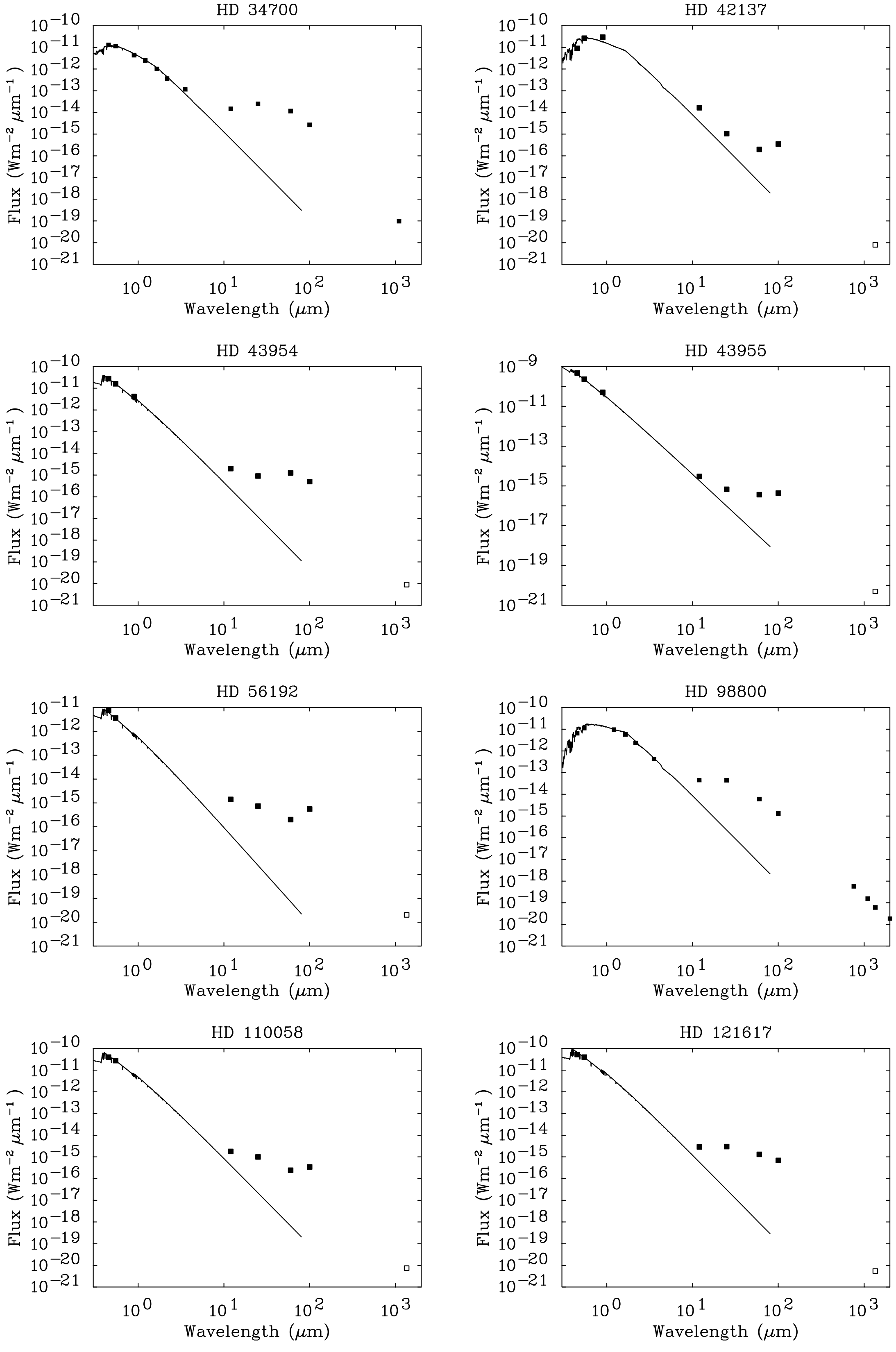

Figure 1. Spectral energy distributions for the stars observed. Open symbols represent upper limits and dotted lines show optically thin radiative transfer models (see text).

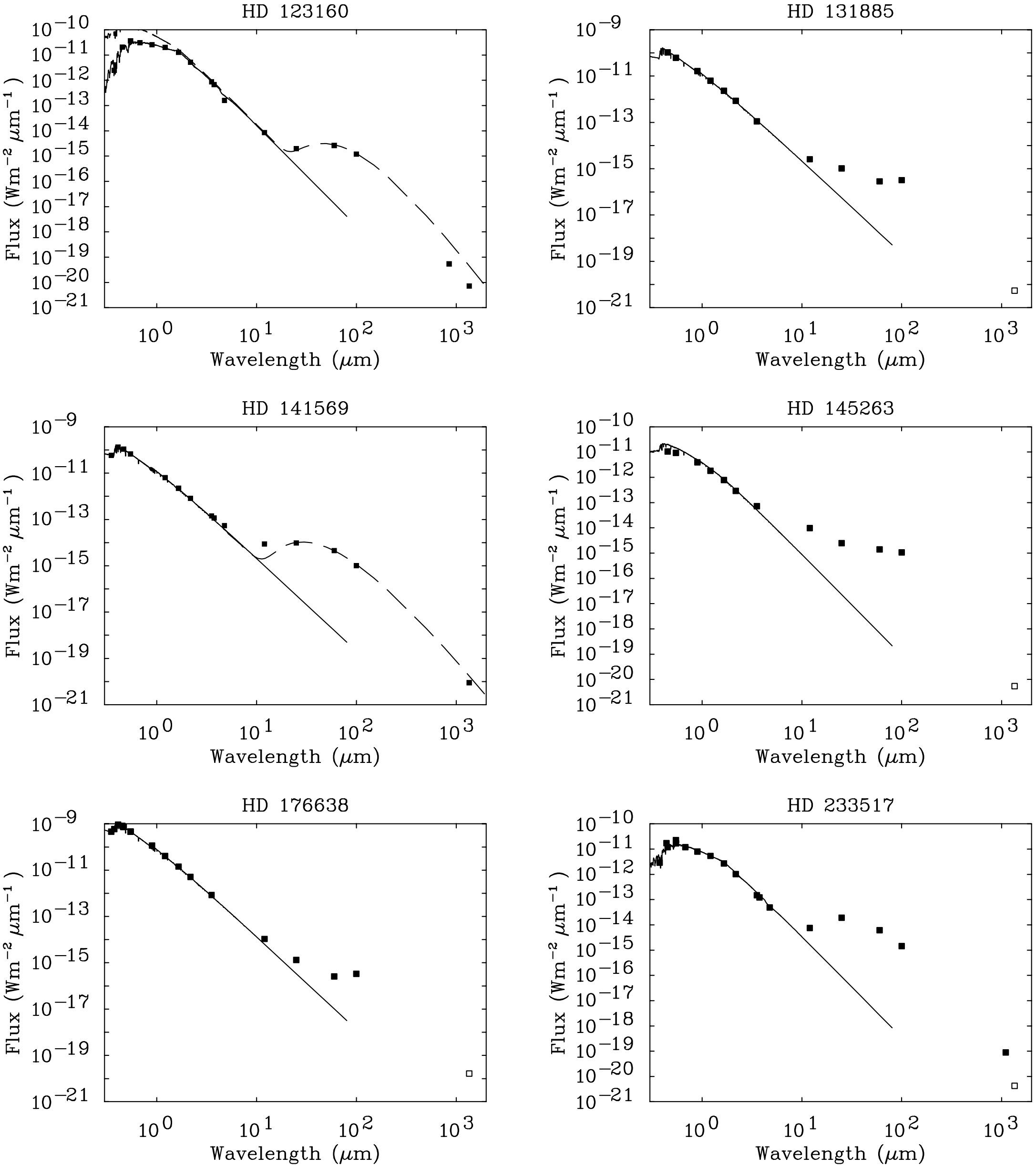

Figure 1 – *continued*

lines in the $\sim \lambda\lambda6449$–6457 wavelength region. Strassmeier & Fekel (1990) show that late-type star luminosities can be estimated using the line ratios of Co I $\lambda6450$/Ca I $\lambda6449$ (for late-G and K stars) and Fe II $\lambda6457$/Ca I $\lambda6456$ (for F and early-G stars). Examination of these ratios for HD 42137 showed that it is indeed a giant star. A spectroscopic study of HD 123160 (SAO 158350) has previously been reported by Dunkin, Barlow & Ryan (1997a), who reclassified the star from K2 (Henry Draper Catalogue) to G5V. In light of the continued uncertainty in its luminosity classification, we looked again at these data, finding that the result reported in Dunkin et al. (1997a) was actually for SAO 158380 (HD 123539) rather than SAO 158350 (HD 123160). Although there is a lack of spectroscopic data for HD 123160, we believe, based on *Hipparcos* measurements, that it is a giant. Giant stars with an infrared excess are of great interest. Zuckerman, Kim & Liu (1995) and Plets et al. (1997) have published lists of luminosity class III stars associated with *IRAS* far-IR dust emission. While Zuckerman et al. estimated that less than 1 per cent of luminosity class III stars (first ascent giants) show evidence for associated dust, by applying a number of statistical estimation methods to their sample, Plets & Vynckier (1999) estimated an occurrence rate of ~ 14 per cent for giants, similar to the occurrence rate estimated for main-sequence stars. Fekel et al. (1996) have studied HDE 233517 (SAO 26804) which had also been previously identified as a Vega-like star (i.e. Skinner et al. 1995) and found that it was actually a giant with a large lithium abundance and far-infrared excess. They suggested (based on other models) that infrared excess, high lithium abundance and rapid rotation may be mutually linked in luminosity class III giants. Jura (1999) examined the possible causes of the dust around these stars. His arguments included sporadic mass loss, diffuse interstellar clouds and appeared to favour the possibility that the dust is a remnant of the main-sequence phase of the star, when it may well have been a Vega-like star. No model has been completely ruled out, and it is clear that these interesting stars deserve further study.

For all of the stars, the IR excess begins at 10–12 μm with no near-IR excess apparent at all. This implies that these systems do not contain any substantial amounts of hot dust in their discs and therefore little dust very close to the star. The same situation also pertains to the prototypical Vega-like systems, whose IR excesses also begin at mid-infrared wavelengths. By contrast, younger objects, such as Herbig Ae/Be stars, tend to show significant near-IR excess emission (e.g. Malfait, Bogaert & Waelkens 1998). HST imaging of some Vega-like systems without near-IR excesses, such as HD 141569 (Augereau et al. 1999, Weinberger et al. 1999) and HR 4796A (Schneider et al. 1999) shows that their discs do indeed have extensive cleared inner regions, which are substantially free of dust.

In most cases, our new mm-wave observations provide a useful extension and/or improvement to existing data, and enable the cooler outer regions of the dusty discs to be modelled with more accuracy. For example, Fig. 1 includes shows the best-fitting radiative transfer models for HD 123160 and HD 141569 from Sylvester & Skinner (1996). The new SCUBA points place important constraints on the models. While the model for HD 141569 is in reasonable agreement with the new data, that for HD 123160 predicts significantly too much mm-wave flux. Given that the model assumed HD 123160 to be a main-sequence star, the assumption that it is in fact a giant star would have a significant effect on the derived grain temperature and mass distributions as a function of distance from the star. HD 141569 has recently been imaged in scattered light (Augereau et al. 1999) and in thermal IR emission (Fisher et al. 2000); these observations, together with the new SCUBA photometry will provide strong constraints for future modelling of this system. The best-fitting radiative transfer model of Sylvester & Skinner (1996) for the dust disk of HD 98800 predicted a 1.35 mm flux of 32 mJy, in agreement with our new measurement of 36.8 ± 4.2 mJy, but their prediction of 13 mJy at 2.00 mm is a factor of two below our measurement of 24.8 ± 3.4 mJy. Sylvester & Skinner's best-fitting model had a maximum grain radius of $a_{\max} = 1$ mm and an $a^{-2.2}$ grain size distribution. A fit to the 2.00 mm flux will require either a larger maximum grain size or a less steep grain size distribution, or both.

The fractional excess luminosities, L_{IR}/L_*, for our stars are shown in Table 2. L_{IR}/L_* is the ratio of the excess IR flux to the total stellar flux, and so is a measure of the fraction of starlight which is absorbed by dust grains. It is dominated by the contribution from the shortest wavelengths at which there is appreciable excess, and thus is rather insensitive to mm-wave fluxes. The values obtained for most of the MB98 stars in Table 2 are $\sim 10^{-3}$, comparable with that of β Pic (2.4×10^{-3}; Backman & Paresce 1993), while HD 43955 has a lower value, similar to those of the other prototype Vega-like stars (e.g. α Lyr 1.5×10^{-5}, α PsA 5.0×10^{-5}; Backman & Paresce 1993). HD 145263 has a large 12-μm excess, giving it the largest L_{IR}/L_* amongst this subset of the MB98 stars. The fractional excess luminosities of the Paper I stars are discussed by Sylvester et al. (1996, 1997). They are often significantly larger than those of the prototype Vega-like stars, reflecting the youthful ages found by Dunkin et al. (1997b) for many of the Paper I objects. From their values of L_{IR}/L_*, we expect most of the MB98 star Vega-like candidates to have ages intermediate between those of the prototypes, such as α Lyr, and the much younger stars of Paper I.

3.1 Spectral indices

The spectral index, α, is defined by $F_\nu \propto \nu^\alpha$ (or $\lambda^{-\alpha}$). The Rayleigh–Jeans (R–J) portion of a blackbody spectrum behaves as $F_\nu \propto \lambda^{-2}$, i.e. $\alpha = 2$. The emissivity of a grain is approximately constant ('grey' emission) at wavelengths shortward of a turnover wavelength, $\lambda_T \approx 2\pi a$, where a is the grain radius. Longwards of λ_T, the emissivity falls as $\lambda^{-\beta}$, where $\beta \approx 1$–2. See Paper I for a fuller description of spectral indices and their interpretation.

The spectral index of a dust disc depends on three factors: the grain emissivity as a function of wavelength (i.e. whether the emissivity has 'turned over'), whether or not the dust disc is optically thick, and whether the blackbody emission from the grains is in the R–J domain. Table 2 shows the spectral indices calculated from the data. Where only upper limits were obtained for the fluxes, we could only calculate lower limits to the spectral indices. For those with lower limit values, most are greater than 2, indicating turned over emission, and are in the Rayleigh–Jeans region. HD 98800 is the only source in our sample where we know for certain that α is less than 2. This indicates that the emission from its coolest grains has not reached the Rayleigh–Jeans domain, and/or that grain sizes in the disc have grown to over 0.3 mm. The fact that most of the other stars have indices greater than two means that the dominant grains in their discs are relatively small.

Our estimates of the spectral index will be compromised if the *IRAS* 100-μm fluxes are not representative of the true 100-μm emission by circumstellar dust, for example if there is significant contamination by Galactic cirrus emission. Examination of the SEDs in Fig. 1 shows that the flux at 100 μm is greater than at 60 μm in many cases, suggesting that the 100-μm points are indeed contaminated (or that there is an additional cold component to the circumstellar dust). Given that the 100-μm fluxes may therefore be unreliable, we have calculated the 60:1300 μm spectral indices, which are also presented in Table 2. The upper limits provided by these spectral indices are noticeably less stringent than the 100:1300 μm limits, so the former tend to be less informative. There are two processes at work here, however: even for sources where the 60-μm flux is higher than the 100-μm flux (e.g. HD 98800, HD 141569) and we do not suspect contamination by cirrus emission, we find that $\alpha_{60:1300}$ is smaller than $\alpha_{100:1300}$. This occurs because the SED is not in the R–J domain at 60 μm, and hence the expected spectral index for large grains is less than 2.0. The $\alpha_{60:1300}$ upper limits can be better exploited by comparing them with the spectral indices derived from blackbodies which fit the observed 25/60 μm flux ratios. These predicted spectral indices, α_{pred} are shown in Table 2. Comparing them with the observed values, we see that for HD 98800, there is good agreement between the predicted and observed spectral indices, indicating that large grains are present around this star, as was inferred both from its 100-μm spectral index and from detailed modelling (Sylvester & Skinner 1996). For eight of our stars, the predicted $\alpha_{60:1300}$ is significantly larger than the observed value (HD 34700, 39944, 123160, 141569) or the upper limit (HD 43954, 121617, 145263, 233517), indicating that large circumstellar grains are not present in significant quantities. For the remaining five stars, the predicted value is below or close to the upper limit, and so conclusions cannot be drawn about the presence of large grains.

3.2 Dust mass estimates

We used the SCUBA results to estimate dust masses and upper limits for our sources, using the formula

$$M_{\mathrm{dust}} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T)}$$

(see e.g. Hildebrand 1982, Mannings 1994), where F_ν is the observed flux, d is the distance to the star, κ_ν is the dust opacity at the frequency of observation and B_ν is the blackbody intensity at the dust temperature, T. We assumed a dust temperature of 30 K for all the sources, and a 1.35-mm dust opacity of $1.07\,\mathrm{cm^2\,g^{-1}}$, (which is equivalent to an 850-μm opacity of $1.7\,\mathrm{cm^2\,g^{-1}}$) and an opacity index $\beta = 1.0$; these values have been adopted by other authors (e.g. Zuckerman & Becklin 1993, Holland et al. 1998, Greaves et al. 1998) for Vega-like systems.

The derived dust masses and upper limits are presented in Table 2. Given that our flux upper limits are rather similar for most of our objects, the severity of the mass upper limits depend on the distances to the stars. The stars at ~ 100 pc distance tend to have mass upper limits of a few $10^{-6}\,\mathrm{M_\odot}$, while those at ~ 300 pc have upper limits an order of magnitude larger. Similarly, the limits for the three stars which may be giants (HD 42137, 123160, 233517) are very large (10^{-5}–$10^{-4}\,\mathrm{M_\odot}$).

Our derived mass estimates can be compared with the dust masses obtained for the prototype Vega-like stars and for related objects. Using the same method, Holland et al. (1998) derived dust masses for Vega, Fomalhaut and β Pic of 2.6×10^{-8}, 5.5×10^{-8} and $2.9 \times 10^{-7}\,\mathrm{M_\odot}$ respectively, while Greaves et al. determined a dust mass of $(1.5\text{–}60) \times 10^{-8}\,\mathrm{M_\odot}$ for ϵ Eri.[1] Mannings & Sargent (1997) estimate that the dust masses for Herbig Ae stars lie in the range $5\text{–}30 \times 10^{-5}\,\mathrm{M_\odot}$, while the range for T Tauri stars is rather similar, at $1\text{–}40 \times 10^{-5}\,\mathrm{M_\odot}$. Our estimates for the MB98 stars show that most of them do not have as much dust as the Herbig or T Tauri stars, and are consistent with (but do not require) dust masses comparable to those of the prototype Vega-like stars. In the case of HD 39944, assuming that the dust is located with the star at 34 pc, the derived dust mass ($6 \times 10^{-7}\,\mathrm{M_\odot}$) is similar to that of β Pic.

The dust masses for the five Paper I stars that we observed can be compared with the values obtained by radiative transfer modelling of the complete SEDs (Skinner et al. 1995, Sylvester & Skinner 1996, Sylvester et al. 1997). The ratios of the model-derived dust mass to the SCUBA value range from 1.5 to 24 for the three detected sources; the relative ordering of these sources in terms of dust mass is the same for both sets of estimates. The two non-detected sources give ratios of < 0.9 (HD 141569) and < 0.6 (HD 233517). Overall, we consider the agreement between the two sets of results to be satisfactory, given the different assumptions made for the dust properties (which are parametrized into the κ value for the SCUBA calculations). The ratios also give an indication of the level of uncertainty inherent in the mass estimates (at least relative to estimates based on more sophisticated models).

4 SUMMARY

The stars in our sample which were taken from the Mannings & Barlow (1998) catalogue appear to have SEDs very similar to those of the prototype Vega-like stars such as Vega and α PsA. They have relatively small infrared excesses compared to the (younger) Vega-excess systems such discussed in Paper I. This suggests that their dust may already have been cleared; the disc systems would therefore be quite evolved. They have large spectral indices in the submillimetre region, indicating that the emission from the grains has already turned over, and that only small grains ($\leqslant 1$ mm) remain in the system. The energy distribution for HD 98800 is qualitatively different. Its spectral index is less than two, indicating that the emission from the dominant grains has yet to reach the Rayleigh–Jeans domain. This implies that grains in this disc are more than 0.3 mm in size, suggesting that significant grain growth has taken place in this system.

Our new SCUBA measurements provide additional constraints on models of the discs around these stars. For example, the previously published models of Sylvester & Skinner (1996) for HD 123160 predict significantly too much 1350-μm flux compared with the new measurement, and hence will have to be revised. The *Hipparcos* parallax data for HD 42137 and HD 123160 suggest that these two stars are giants, rather than main-sequence stars. As discussed earlier, Fekel et al. (1996) have previously reclassified the Vega-like candidate HD 233517 from a dwarf to a giant star, so HD 42137 and HD 123160 would join a growing number of first ascent giants confirmed to exhibit circumstellar dust emission.

ACKNOWLEDGMENTS

We would like to thank Ian Crawford for allowing us access to data prior to publication. This work made use of the Starlink computing network, funded by the Particle Physics and Astronomy Research Council (PPARC), UK. SKD carried out this work while funded as a PPARC Research Fellow. Use was made of the Simbad data base and other facilities maintained at the CDS, Strasbourg. The JCMT is operated by the Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council, the Netherlands Organization for Pure Research, and the National Research Council of Canada.

REFERENCES

Abt H. A., Gomez A. E., Levy S. G., 1990, ApJS, 74, 551
Augereau J. C., Lagrange A. M., Mouillet D., Ménard F., 1999, A&A, 350, L51
Aumann H. H. et al., 1984, ApJ, 278, L23
Backman D. E., Paresce F., 1993, in Levy E. H., Lunine J. I. eds, Protostars & Planets III. Univ. Arizona, Tucson, p. 1253
Bushouse H., Telesco C. M., Werner M. W., 1998, AJ, 115, 938
Dent W. R. F., Walker H. J., Holland W. S., Greaves J. S., 2000, MNRAS, 314, 702
Dunkin S. K., Barlow M. J., Ryan S. G., 1997a, MNRAS, 286, 604
Dunkin S. K., Barlow M. J., Ryan S. G., 1997b, MNRAS, 290, 165
ESA, 1997, The *Hipparcos* and *Tycho* Catalogues. ESA SP-1200
Fekel F. C., Webb R. A., White R. J., Zuckerman B., 1996, ApJ, 462, L95
Fisher R. S., Telesco C. M., Piña R. K., Knacke R. F., Wyatt M. C., 2000, ApJL, 532, 141
Greaves J. S. et al., 1998, ApJ, 506, L133
Hildebrand R. H., 1982, QJRAS, 24, 267
Holland W. S. et al., 1998, Nat, 392, 788
Holland W. S. et al., 1999, MNRAS, 303, 659
Jura M., 1999, ApJ, 515, 706
Lagage P. O., Pantin E., 1994, Nat, 369, 628
Lauberts A., 1982, The ESO/Uppsala Survey of the ESO(B) Atlas. ESO, Garching bei München

---

[1] Detailed radiative transfer modelling of these systems by Dent et al. (2000) yielded dust masses which, although in agreement with the Holland et al. estimate for Fomalhaut, were three times lower in the cases of Vega and β Pic and more than five times lower in the case ϵ Eri. The radiative transfer modelling of the dust disc of HD 98800 by Sylvester & Skinner (1996) yielded a disc mass estimate of 3.8×10^{-7}, 25 times lower than the value obtained in Table 2. Therefore the disk masses in Table 2 are likely to be overestimates but may provide a useful indicator of relative trends.

Malfait K., Bogaert E., Waelkens C., 1998, A&A, 331, 211
Mannings V., 1994, MNRAS, 271, 587
Mannings V., Barlow M. J., 1998, ApJ, 497, 341, (MB98)
Mannings V., Sargent A. I., 1997, ApJ, 490, 792
Moshir M. et al., 1992, Explanatory Supplement to the *IRAS* Faint Source Survey, Version 2, JPL D-10015 8/92. JPL, Pasadena
Plets H., Vynckier C., 1999, A&A, 343, 496
Plets H., Waelkens C., Oudmaijer R. D., Waters L. B. F. M., 1997, A&A, 323, 513
Schmidt-Kaler Th., 1982, in Schaifers K., Voigt H. H., eds, Landolt-Börnstein, Numerical Data and Functional Relationships in Science and Technology, Group VI, Astronomy, Astrophysics and Space Research, Vol. 2b. Springer-Verlag, Berlin, p. 14
Schneider G. et al., 1999, ApJ, 513, L127
Skinner C. J., Sylvester R. J., Graham J. R., Barlow M. J., Meixner M., Keto E., Arens J. F., Jernigan J. G., 1995, ApJ, 861, 873
Smith B. A., Terrile R. J., 1984, Sci, 226, 1421
Strassmeier K. G., Fekel F. C., 1990, A&A, 230, 389
Sylvester R. J., Mannings V., 2000, MNRAS, 313, 73
Sylvester R. J., Skinner C. J., 1996, MNRAS, 283, 457
Sylvester R. J., Barlow M. J., Skinner C. J., Mannings V., 1996, MNRAS, 279, 915 (Paper I)
Sylvester R. J., Barlow M. J., Skinner C. J., 1997, MNRAS, 289, 831
Walker H. J., Butner H. M., 1995, Ap&SS, 224, 389
Walker H. J., Wolstencroft R. D., 1988, PASP, 100, 1509
Weinberger A. J., Becklin E. E., Schneider G., Smith B. A., Lowrance P. J., Silverstone M. D., Zuckerman B., Terrile R. J., 1999, ApJ, 525, L53
Zuckerman B., Becklin E. E., 1993, ApJ, 414, 793
Zuckerman B., Kim S. S., Liu T., 1995, ApJ, 446, L79

This paper has been typeset from a TEX/LATEX file prepared by the author.