Submillimetre observations and modelling of Vega-type stars

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ABSTRACT
We present new submillimetre observations of Vega-excess stars, and consistent modelling for all known Vega-excess stars with submillimetre data. Our analysis uses dust grain models with realistic optical properties, with the aim of determining physical parameters of the unresolved discs from just their spectral energy distributions (SEDs). For the resolved targets, we find that different objects require very different dust grain properties in order to fit the image data and SED simultaneously. Fomalhaut and Vega require solid dust grains, while HR 4796 and HD 141569 can only be fitted using porous grains. The older stars tend to have grains which are less porous than the younger stars, which may indicate that collisions in the discs have reprocessed the initially fluffy grains into a more solid form. $\epsilon$ Eri appears to be deficient in small dust grains compared with our best-fitting model. This may show that it is important to include all the factors that cause the size distribution to depart from a simple power law for grains close to the radiation pressure blow-out limit. Alternatively, this discrepancy may be due to some external influence on the disc (e.g. a planet).

When the model is applied to the unresolved targets, an estimate of the disc size can be made. However, the large diversity in dust composition for the resolved discs means that we cannot make a reliable assumption as to the composition of the grains in an unresolved disc, and there is corresponding uncertainty in the disc size. In addition, the poor fit for $\epsilon$ Eri shows that the model cannot always account for the SED even if the disc size is known. These two factors mean that it may not be possible to determine the size of a disc without actually resolving it.

Key words: circumstellar matter – dust, extinction.

1 INTRODUCTION
In 1983, the IRAS satellite detected a large infrared excess from Vega ($\alpha$ Lyr) during a routine calibration observation (Aumann et al. 1984). Soon, a similar excess was detected from three more stars ($\beta$ Pic, Fomalhaut and $\epsilon$ Eri). The excess could only be explained by a shell or ring of dust, heated to between 50 and 125 K by the central star. Quite by accident, IRAS had uncovered the first examples of solid material orbiting a normal main-sequence star other that our own Sun.

The four stars mentioned above have become the prototypes for the ‘Vega excess’ phenomenon (Backman & Paresce 1993; Lagrange, Backman & Artymowicz 2000). A systematic study of the IRAS all-sky survey shows that around 15 per cent of all main-sequence stars have an infrared (IR) excess due to circumstellar dust (Dominik & The Hjhvega Consortium 1997; Fajardo-Acosta et al. 1999). Coronographic and submillimetre imaging has shown the dust is typically in a ring or disc geometry (Smith & Terrile 1984; Holland et al. 1998) and that these systems have much in common with our own solar system, i.e. solid material in stable coplanar orbits distributed within a region roughly the size of the Kuiper belt.

Though the Vega phenomenon is common, the poor resolution of current far-IR and submillimetre instruments means that few Vega-excess stars are close enough to be resolved. For the cases where the discs are resolved, detailed analysis using realistic models for the optical properties and size distribution of the dust can be performed. This type of work has been attempted for $\beta$ Pic (Li & Greenberg 1998a), HR 4796 (Augereau et al. 1999b; Li & Lunine 2003a) and Fomalhaut (Wyatt & Dent 2002). These models use the observed spatial distribution of dust, and fit the spectral energy distribution (SED) by varying the dust composition and size distribution. However, as these objects have been analysed on a case-by-case basis, different models and assumptions are used, which makes it somewhat difficult to make direct comparisons. In addition, there are so few resolved targets that it is impossible to look for statistical trends between disc size, age, stellar mass, etc. However, there are many unresolved targets with good SED information, and new instruments such as SIRTF and SOFIA will produce many more such
objects. A method which could retrieve the physical parameters of a disc from just its SED would be invaluable. To accomplish this, the detailed properties of the dust grains in Vega-excess discs must be fully understood.

We have tried to tackle these problems in two ways. First, we have made submillimetre photometric observations of Vega-excess stars, to help constrain their SEDs. Secondly, we have attempted to model all known Vega-excess stars with submillimetre data, using a consistent model with realistic dust grains. This allows us to compare directly the results of modelling for resolved targets, and use the knowledge of dust grain size and composition gained to estimate the disc size for the unresolved targets.

2 OBSERVATIONS

Submillimetre observations were made using the Submillimetre Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT). The observations were made as part of several different observing programmes, and hence data were obtained in different observing modes. In addition, we have reduced unpublished archive observations of suspected Vega-excess stars to enlarge our sample. The observations are summarized in Table 1 and the parameters for the stars are shown in Table 2.

SCUBA can be used in two ways, either for photometry or for mapping. The distinction arises because the bolometers are spaced too widely to sample the image fully at the focal plane. Therefore in mapping mode, the moving secondary mirror is used to add slight offsets to the telescope pointing, and hence mapping mode, the moving secondary mirror is used to add slight offsets to the telescope pointing, and hence

| Object      | Date          | Wavelength | Mode   |
|-------------|---------------|------------|--------|
| HD 17206    | 1997 Aug 23   | 450/850    | Map    |
| HD 17206    | 1997 Aug 27   | 450/850    | Map    |
| HD 23362    | 2000 Jun 7    | 450/850    | Map    |
| HD 34282    | 1997 Sep 25   | 450/850    | Map    |
| HD 34700    | 1997 Aug 14   | 450/850    | Map    |
| HD 35187    | 1997 Dec 13   | 450/850    | Map    |
| HD 38393    | 2001 Mar 11   | 450/850    | Ext. Phot. |
| HD 48682    | 2001 Mar 9    | 450/850    | Ext. Phot. |
| HD 69830    | 2001 Mar 9    | 450/850    | Ext. Phot. |
| HD 81515    | 2000 Mar 21   | 450/850    | Map    |
| HD 109085   | 2000 Mar 21   | 450/850    | Map    |
| HD 121617   | 1998 Feb 19   | 450/850    | Ext. Phot. |
| HD 123160   | 1997 Dec 9    | 450/850    | Photometry |
| HD 128167   | 2002 Jan 21   | 450/850    | Ext. Phot. |
| HD 139664   | 1997 Nov 30   | 450/850    | Map    |
| HD 207129   | 1998 May 17   | 450/850    | Map and Photometry |
| HD 207129   | 1998 May 28   | 450/850    | Map    |

3 DATA REDUCTION

3.1 Photometry data

Photometry data were reduced using the SURF package. After combining the positive and negative beams, the data were flat-fielded and corrected for atmospheric extinction, estimated using a polynomial fit to the Caltech Submillimeter Observatory (CSO) 225-GHz opacity monitor and the relations in Archibald, Wagg & Jenness (2000). Residual sky emission was estimated using bolometers well separated from the source, and this signal was subtracted from the data. The sky bolometers were those in rings 2 and 3 (30 bolometers in total), and their median was taken as the average sky signal. The signal from the central bolometer was then despiked using a 4σ cut.

Calibration sources were observed and reduced in exactly the same way as the targets. If a planet was used as a calibrator, the FLUXES package was used to estimate the flux and a correction was made for the loss of flux because the object was resolved. For the observations taken with the extended photometry mode, all of the calibration sources were point-like (i.e. secondary calibrators, not planets). Thus the final photometry is derived under the assumption that the emission is point-like and centred on the star. If a target is extended (i.e. marginally resolved) or is offset from the position of...
Map data were reduced using custom data-reduction software written in IDL. This system is similar to that developed to reduce data for the 8-mJy extragalactic survey (Scott et al. 2002). This method is preferred over the SURF software because the residual sky emission is removed more effectively (a plane is fitted to the residual emission, rather than a constant), and the ‘zero footprint’ rebinning method produces a map where each pixel is an independent measurement, which makes subsequent analysis much simpler. Source flux was measured by fitting an elliptical Gaussian to the source. To ensure that the software was reliable, SURF was used to reduce several sources, and the results from the two reduction systems were compared to ensure that any differences were well within the errors.

Calibration was done by calculating the flux conversion factor from the peak flux of a Gaussian fit to calibration sources. Using the peak signal rather than the integrated signal means that the measurement is sensitive to changes in the beam shape (Dunne & Eales 2001), but this approach was necessary as most of the calibration sources were secondary calibrators, and only the peak signal is well-determined for these sources.

### 4 RESULTS

The results of the submillimetre observations are shown in Table 4. For objects with multiple observations, the flux given is the weighted mean of all the data. Of the 15 objects observed, seven were not detected, four were detected at 850 and 450 μm, and four were detected at 850 μm only.

Most of the objects have not been observed in the submillimetre before, but for objects with existing observations, the new data were checked for consistency with the old results. HD 34282 and HD 35187 have both been observed with UKT14 (Sylvester et al. 1996): HD 34282 had a flux of 1.3 ± 0.3 Jy at 400 μm and 0.409 ± 0.027 Jy at 800 μm; HD 35187 had a flux of 0.115 ± 0.022 Jy at 800 μm. The discrepancy between these fluxes and the new data is small (2σ), however similar discrepancies have been found in other comparisons of UKT14 and SCUBA data (e.g. Sylvester, Dunkin & Barlow 2001). This may be due to calibration errors in the original data.

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### Table 2.

Parameters of stars used in our analysis. The top part of the table shows objects with new submillimetre data; the bottom part shows objects where we have analysed published data. Spectral type and distance are from SIMBAD.

| Object   | Other name | Spectral type | Distance pc | \( L_{\text{data}} / L_{\text{star}} \) | Reference | Estimated age Myr | Reference |
|----------|------------|---------------|-------------|---------------------------------|-----------|------------------|-----------|
| HD 17206 | F3/F6V     |               | 13.97       |                                 |           |                  |           |
| HD 23362 | K2         |               | 308.6       | \( 7.9 \times 10^{-4} \)         | 1         |                  |           |
| HD 34282 | A0         |               | 163.9       | 0.39                            | 1         |                  |           |
| HD 34700 | G0         |               | >180        | 0.14                            | 2         |                  |           |
| HD 35187 | A2         |               | 150         | 0.14                            | 1         |                  |           |
| HD 38393 | F7V        |               | 8.97        | \( 5.3 \times 10^{-6} \)         | Best-fitting model | 1660+1580−1991 | 8         |
| HD 48682 | G0V        |               | 16.4        | \( 1.2 \times 10^{-4} \)         | Best-fitting model |           |           |
| HD 69830 | K0V        |               | 12.58       | \( 2.3 \times 10^{-4} \)         | Spline    | 600-2000         | 10        |
| HD 81515 | A5Vm...    |               | 107.0       |                                 |           |                  |           |
| HD 109085| F2V        |               | 18.2        | \( 4 \times 10^{-4} \)           | Spline    |                  |           |
| HD 121617| A1V        |               | 180+        | \( 4.5 \times 10^{-5} \)         | 2         |                  |           |
| HD 123160| K5         |               | >250        |                                 |           |                  |           |
| HD 128167| σ Boo      | F2V           | 15.5        | \( 1.8 \times 10^{-5} \)         | Best-fitting model | 1700+1320−720 | 8         |
| HD 139664| F3IV-V     |               | 17.5        | \( 1.9 \times 10^{-4} \)         | Spline    | 1120+880−875     | 8         |
| HD 141569| B9         |               | 99.0        | \( 8.3 \times 10^{-5} \)         | 2         | 5 ± 3            | 7         |
| HD 207129| G0V        |               | 15.6        | \( 1.0 \times 10^{-4} \)         | Spline    | 6030+2290−1660   | 8         |
| HD 22049 | ε Eri      | K2V           | 3.22        | \( 1.1 \times 10^{-4} \)         | Best-fitting model | 730 ± 200  | 10        |
| HD 39060 | β Pic      | A5V           | 19.3        | \( 3 \times 10^{-3} \)           | 3         | 20 ± 10          | 6         |
| HD 109573| HR 4796    | A0V           | 67          | 0.005                            | 4         | 8 ± 2            | 9         |
| HD 172167| Vega       | A0V           | 7.76        | \( 2 \times 10^{-5} \)           | 3         | 354+29−37        | 5         |
| HD 216956| Fomalhaut  | A3V           | 7.69        | \( 8 \times 10^{-5} \)           | 3         | 156+188−106      | 5         |

*Spline fits to the residual flux distribution.*

Reference list: (1) Sylvester et al. (1996); (2) Sylvester et al. (2001); (3) Backman & Paresce (1993); (4) Jura (1991); (5) Song et al. (2001); (6) Barrado y Navascués et al. (1999); (7) Weinberger et al. (2000); (8) Lachaume et al. (1999); (9) Stauffer et al. (1995); (10) Song et al. (2000).

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### Table 3.

Comparison of the three photometry modes, showing the effect of an extended or offset Gaussian source. The table shows the ratio of the quoted flux density to the true flux density. The point spread function FWHM is assumed to be 14 arcsec.

| Offset arcsec | FWHM arcsec | Normal | Ext. 9 pt. | Ext. 12 pt. |
|--------------|-------------|--------|-----------|------------|
| 0            | 0           | 1.00   | 1.00      | 1.00       |
| 0            | 5           | 0.89   | 0.93      | 0.92       |
| 0            | 10          | 0.68   | 0.76      | 0.75       |
| 5            | 0           | 0.72   | 0.81      | 0.79       |
| 5            | 5           | 0.67   | 0.76      | 0.75       |
| 5            | 10          | 0.54   | 0.65      | 0.63       |
| 10           | 0           | 0.27   | 0.41      | 0.40       |
| 10           | 5           | 0.28   | 0.41      | 0.39       |
| 10           | 10          | 0.28   | 0.39      | 0.37       |

the star, then observations in photometry mode will underestimate the true flux, by an amount shown in Table 3. As expected, the extended photometry modes are less affected than the conventional photometry mode.

### 3.2 Maps

Map data were reduced using custom data-reduction software written in IDL. This system is similar to that developed to reduce data for the 8-mJy extragalactic survey (Scott et al. 2002). This method is preferred over the SURF software because the residual sky emission is removed more effectively (a plane is fitted to the residual emission, rather than a constant), and the ‘zero footprint’ rebinning method produces a map where each pixel is an independent measurement, which makes subsequent analysis much simpler. Source flux was measured by fitting an elliptical Gaussian to the source. To ensure that the software was reliable, SURF was used to reduce several sources, and the results from the two reduction systems were compared to ensure that any differences were well within the errors.

Calibration was done by calculating the flux conversion factor from the peak flux of a Gaussian fit to calibration sources. Using the peak signal rather than the integrated signal means that the measurement is sensitive to changes in the beam shape (Dunne & Eales 2001), but this approach was necessary as most of the calibration sources were secondary calibrators, and only the peak signal is well-determined for these sources.
Table 4. Photometry results and estimated dust masses for our sample. The top part of the table shows new data, and the bottom part shows existing data. The dust temperature is estimated from the wavelength of maximum emission for the best-fitting SED model. HD 34700 has a lower limit on its distance, and hence we calculate a lower limit on its dust mass. These mass estimates are consistent with existing estimates made for Fomalhaut, Vega and β Pic in Holler et al. (1998) and for eEri in Greaves et al. (1998).

| Object       | 450 μm Flux (Jy) | 850 μm Flux (Jy) | T_dust (K) | M_dust (Moon) |
|--------------|------------------|------------------|------------|---------------|
| HD 17206     | <0.1789          | <0.0078          | <0.33       |
| HD 23362     | <0.17            | <0.012           | <2.1        |
| HD 34282     | 1.925 ± 0.29     | 0.384 ± 0.023    | 3 × 10^{11} |
| HD 34700     | 0.218 ± 0.037    | 0.0407 ± 0.0024  | >286        |
| HD 35187     | 0.268 ± 0.047    | 0.061 ± 0.005    | 298         |
| HD 38393     | <0.0428          | 0.0024 ± 0.001   | 82          |
| HD 48682     | <0.0368          | 0.0055 ± 0.0011  | 99          |
| HD 69830     | <2.0248          | <0.1005          | <3.5        |
| HD 81515     | <0.26            | <0.02            | <49.7       |
| HD 109065    | <0.0381          | 0.0075 ± 0.0012  | 85          |
| HD 121617    | <0.36            | <0.02            | 85          |
| HD 123160    | 0.152 ± 0.046    | 0.021 ± 0.007    | <1.0        |
| HD 139664    | <0.39            | <0.015           | <1.0        |
| HD 141569    | 0.066 ± 0.023    | 0.014 ± 0.002    | 90          |
| HD 207129    | <1.7             | <0.018           | <0.95       |
| σ Boo        | 0.0062 ± 0.0017  | 62               |
| e Eri        | 0.225 ± 0.010    | 0.040 ± 0.0015   | 85          |
| β Pic        | 0.104 ± 0.010    | 103              |
| HR 4796      | 0.180 ± 0.15     | 0.0191 ± 0.0034  | 99          |
| Vega         | 0.0457 ± 0.0054  | 68               |
| Fomalhaut    | 0.595 ± 0.035    | 0.097 ± 0.005    | 75          |

αCalculated assuming a dust temperature of 100 K.
βTaken from Piétu, Dutrey & Kahane (2003).
γSubmillimetre emission is offset by 9 arcsec from the star, and is thought to be due to a galaxy (see Section 4).

For the purposes of this paper, the extended photometry observations have been reduced in exactly the same way as conventional photometry, so the result of the data reduction is just the total flux. However, the data also contain some spatial information, and more complicated reduction will give some indication of the size of the disc as well as its flux. This will be tackled in a subsequent paper (Wyatt et al., in preparation).

One of the advantages of SCUBA observations is that they can confirm that the IRAS excess is associated with the star, and not simply a background source (i.e. a galaxy or galactic cirrus). Contamination by background sources is a significant problem, and follow-up observations are important to confirm that the IRAS associations are real. Certainly, not all IRAS associations are real, as demonstrated by observations of 55 Cnc (Jayawardhana et al. 2002) and HD 155826 (Lisse et al. 2002). SCUBA is a useful tool for confirming associations because it gives source positions which are significantly more accurate than those from IRAS. IRAS detections have a typical positional uncertainty of about 16 arcsec in the cross-scan direction and 3 arcsec in the in-scan direction (Beichman et al. 1988). In map mode, SCUBA positional uncertainties are about 2 arcsec for bright sources, limited only by the pointing accuracy of the dish. In photometry mode, the positional accuracy is determined by the size of the beam [full width at half-maximum (FWHM) of 14 arcsec] so these observations are less useful for this purpose. From our sample, one object was rejected on the basis of its submillimetre position: HD 123160 was a strong SCUBA detection, but the source seemed to be offset from the stellar position by about 10 arcsec. In addition, this star is now thought to be a distant class III giant (Kalas et al. 2002), and there is evidence of several galaxies in the optical Digital Sky Survey image. This indicates that the IRAS source is probably a background galaxy.

SCUBA is also sensitive to background galaxies, and so there is a possibility that a background galaxy could fall into the beam of the observations and cause a spurious detection. The chances of this happening depend on the limiting flux of the observations (as there are many more faint galaxies than bright ones) and the size of the beam. The extended photometry mode is therefore more susceptible to this problem, as it is sensitive to sources over ~2 times more area than conventional photometry. The tentative detection of HD 38393 has the highest probability of being due to a background galaxy, as the source is extremely faint and the observations were taken in extended photometry mode. This possibility is discussed further in Section 6.8.

The mass of the discs was estimated from the 850-μm flux, using a dust temperature determined from the peak of the dust emission SED, and this is shown in Table 4. We set the mass absorption coefficient \( \kappa = 1.7 \text{ cm}^2 \text{ g}^{-1} \) at 850 \( \mu \text{m} \) for consistency with previous work (e.g. Zuckerman & Becklin 1993; Hollond et al. 1998; Sylvester et al. 2001). Detailed discussion of the value of \( \kappa \) can be found in Pollack et al. (1994). It is important to note that this mass estimate cannot measure the mass held in grains larger than about 1 mm. This is a key point, as in a collisional cascade (see Section 5.3) the total mass of the disc is dominated by the contribution from large bodies, which contribute little to the 850-μm emission. Our mass estimate only reflects the amount of mass held in small dust grains, and even then is model-dependent. The dust masses of the new targets are comparable with those measured in previous studies, ranging from 0.04 lunar masses (HD 38393) to 33 lunar masses (HD 141569) for the Vega-excess stars, and hundreds of lunar masses or more for the pre-main-sequence stars (HD 34700, HD 35187 and HD 34282).

5 SED MODELLING

Our key objective is to determine the size of a Vega-excess disc from just its SED. Because models have many free parameters, we have tried to constrain the models as much as possible using our understanding of the physical processes taking place in the discs, in particular by setting the size distribution from theoretical arguments.

The model used here is a modified version of the model developed to fit the SED and submillimetre image of Fomalhaut (Wyatt & Dent 2002), and a more detailed description can be found there. The model is based on a collisional cascade, where small dust grains are continuously created by collisions between larger bodies. The only significant difference between the model used here and that used by Wyatt & Dent (2002) is that we use a simpler assumption about the spatial distribution of the dust (see Section 5.4 for details).

For this model to be accurate, the disc must be optically thin to radiation from the central star. If this is not the case, then the inner parts of the disc will shadow the outer parts from starlight, and a radiative transfer code would be needed to model the system properly. We have therefore excluded all the objects where \( L_{\text{dust}}/L_{\text{star}} > 0.1 \). This ensures that discs are optically thin, as long as the opening angle is more than 2°. Measured opening angles are generally larger than this, e.g. 7° for β Pic (Heap et al. 2000). HD 34282, HD 34700 and HD 35187 all have \( L_{\text{dust}}/L_{\text{star}} > 0.1 \), so these objects have not been included in our analysis.

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5.1 Photometric data

Mid- and far-IR photometry data are taken from the IRAS faint-source catalogue (Moshir et al. 1990). Where available, these are supplemented by ground-based mid-IR data from the literature. Also, published ISO photometry has been added to help constrain the far-IR part of the SEDs (in particular data from Habing et al. 2001).

5.2 Dust grain properties

Our model of the dust grains is based on the assumption that the grains in protoplanetary discs are aggregates of interstellar dust grains, with an additional ice component frozen into them as they grow. This type of model was originally developed to simulate cometary grains (Greenberg 1982, 1998), but it has also been successfully applied to the dust grains in accretion discs (Pollack et al. 1994), and to the debris discs of β Pic (Li & Greenberg 1998a), HR 4796 (Augereau et al. 1999b; Li & Lunine 2003a), HD 141569 (Li & Lunine 2003b) and HD 207129 (Jourdain de Muizon et al. 1999).

For the composition of the interstellar grains, we use the core–mantle model developed in Li & Greenberg (1997), which successfully fits the observed interstellar extinction and polarization. This model has a silicate core surrounded by an ultraviolet (UV)-processed organic refractory mantle. We force the silicate/organic-refractory volume ratio to be 1:2, as inferred for cometary grains (Greenberg 1998). The grains are assumed to be porous, with the porosity being a free parameter of the model. For dust grains cooler than ~120 K, the gaps due to porosity may be filled with either vacuum, water ice or a mixture of the two; for dust grains warmer than ~120 K most ices would sublime, so the gaps must be filled with vacuum. The free parameters in the dust composition model are therefore the porosity $p$ of the grains and the ice fraction $q_{\text{ice}}$, with the constraint that for warm grains the ice fraction must be zero.

Optical constants for the materials are taken from Li & Greenberg (1997, 1998a). The optical constants for the composite dust grain material are then calculated using Maxwell–Garnet effective medium theory. Then, the absorption efficiencies for the dust grains are calculated using Mie theory, Rayleigh–Gans theory, or geometric optics, depending on the size of the dust grain. Details of Maxwell–Garnet effective medium theory, and the methods used to calculate absorption efficiencies, are discussed in Bohren & Huffman (1983).

5.3 Size distribution

The size distribution that results from an infinite collisional cascade is (Dohnanyi 1969):

$$n(D) \propto D^{2-3q},$$  \hspace{1cm} (1)

where $n(D)\,dD$ is the number of planetesimals of size between $D$ and $D + dD$, and $q = 11/6$. However, this distribution will only hold for large dust grains, as radiation pressure will blow out small grains (e.g. <1 μm) very rapidly, and Poynting–Robertson (PR) drag will cause intermediate sized grains (e.g. <10 μm) to spiral inwards toward the star. Which of these two effects is dominant depends on the optical depth of the dust disc, but for all but the most tenuous discs the collisional time-scale is shorter than the PR time-scale, so PR drag can be safely ignored (Wyatt et al. 1999). Given this, we assume that the above size distribution holds down to the radiation blow-out limit, when $\beta > 0.5$ (where $\beta = F_{\text{rad}}/F_{\text{grav}}$), at which point there is a sharp cut-off.

5.4 Spatial distribution

For the spatial distribution of the dust grains, we assume an infinitely thin, flat ring, with the radius of the ring, $R$, as a free parameter. This approach is motivated by the submillimetre images of Fomalhaut and e Eri, which both show a narrow, well-defined ring of emitting material. This spatial distribution is different from that used in Wyatt & Dent (2002), as here no attempt is made to account for the eccentricities of the dust grains, which broadens the ring by about 50 au. The advantage of the simpler model is that it reduces the number of free parameters, but should still give a reasonable estimate of the overall extent of the disc. The Fomalhaut results from the two versions of the model are almost identical (see Section 6.1), which gives us confidence that this simplification will not affect our conclusions.

5.5 Stellar parameters

Accurate stellar parameters are needed for several reasons. First, the photospheric flux must be estimated in each band, so that the excess flux due to dust can be determined. This is particularly important in the IRAS 12- and 25-μm bands, where the photosphere can be the dominant source of flux. Secondly, the temperature of the dust depends on the luminosity of the star, and on the shape of the spectrum of the star in the region where most power is emitted (i.e. UV–optical–near-IR). The luminosity and stellar spectrum also determine the magnitude of the radiation forces which act on the dust grains. Finally, an estimate of the mass of the star is needed to calculate the gravitational forces.

To determine the stellar parameters, we first obtained the spectral type of each star from SIMBAD. This was used to estimate the effective temperature of the star, using the calibration provided in Gray & Corbally (1994). We then extracted a Kurucz model atmosphere with this effective temperature, assuming solar metallicity and surface gravity $\log(g) = 4.3$ appropriate for dwarf stars. The model atmosphere was then normalized to fit the $K$-band magnitude. $K$ band was preferred over optical photometry because it is less susceptible to the effects of reddening. The luminosity of the star was then calculated by integrating the normalized model atmosphere. Finally, the mass of the star was estimated using the observed spectral type and the table provided by Lang (1992, page 132).

5.6 Modelling method

A model SED is specified by the grain composition (porosity $p$, ice fraction $q_{\text{ice}}$), radius of the dust ring ($R$), and the total dust luminosity. In the case where the size of the dust ring is known, the ring radius is fixed to the observed size; for the unresolved objects the ring radius is left as a free parameter. The approach we take is to choose a dust composition, and then find the best fit to the data by varying the remaining free parameters.

The emission spectrum of an individual dust grain depends on its temperature and on the emission efficiency as a function of wavelength. The SED of a disc is simply the combined emission of all the dust grains. For a given dust composition model, the absorption efficiency is calculated as a function of grain size. Given this, the temperature of the dust grains as a function of grain size and distance from the star can be determined. Then, the total flux as a function of wavelength is found by integrating over all grain sizes, weighting with the size distribution given in equation (1).

The model spectrum is then converted into an SED that can be directly compared to the observed points to obtain a $\chi^2$ value. To do
this, the spectral response of each filter–instrument combination is multiplied by the model spectrum, to estimate the broad-band flux that would be recovered from a real observation of the model spectrum. This step is particularly important for the IRAS data points, which have a very wide bandpass. By converting the model spectrum into broad-band fluxes, we avoid having to make colour correction to the original data, which would otherwise require detailed knowledge of the true spectrum of the source. However, when showing the result of the fit, a colour correction must be applied so that the data points can be plotted in real units. For this purpose, the best-fitting model is used to estimate the colour correction for each point. If the best model is more than 3σ away from a data point, then no colour correction is applied to that point, as the model is not likely to give a good estimate of the true colour correction. The fitted parameters and χ² are shown in Table 5, and the colour-corrected IRAS fluxes are given in Table 6.

For some objects it is impossible to fit all the data points simultaneously, because there is dust at a range of distances from the star. In these cases, only the long-wavelength points are fitted, in order to obtain an estimate of the overall extent of the ring.

6 MODELLING RESULTS

6.1 Fomalhaut

The size of the dust disc of Fomalhaut is known from the submillimetre images made with SCUBA (Holland et al. 2003). Because the ring is inclined and the images have low resolution, the size of the ring cannot be measured directly from the images, but the best estimate of the true size is 150 au (Wyatt & Dent 2002). The SED data for Fomalhaut come from IRAS, SCUBA and also ISO. The ISO fluxes are from Walker et al. (in preparation), and are listed in Wyatt & Dent (2002).

Our modelling (Fig. 1) shows a good fit for solid dust grains (i.e. p = 0.0), but rules out porous grains as this would make the dust hotter than is observed. The p = 0.5, q_{ice} = 1.0 model is also ruled out, as it fails to fit the mid-IR part of the SED.

The reduced χ² for the best-fitting model is 4.2, which indicates that the model is not consistent with the data. However, by far the dominant contribution to χ² comes from the ISO data, which show considerable scatter from any smooth model. The ISO filters all have broad bandpasses (Δλ/λ ~ 0.5), so the apparent scatter in the ISO points is unlikely to be due to structure in the spectrum. A more likely explanation is that uncertainties on the ISO points have been underestimated, and this would explain the high reduced χ².

Fomalhaut has already been modelled in detail by Wyatt & Dent (2002), and the results here are almost identical to those results. As the modelling here uses the same data and dust grain model, it is hardly surprising that we recover the same results. However, this does confirm that the simpler spatial distribution used here does not significantly affect the results of the modelling.

6.2 HR 4796

HR 4796 is resolved in both mid-IR images of dust emission (Jayawardhana et al. 1998; Koerner et al. 1998) and scattered light images in the near-IR (Schneider et al. 1999). The best estimate of the size of the ring comes from mid-IR images, which suggest that the radius is 70 au. The star is younger than most of the other stars in the sample, with an age of 8 ± 2 Myr (Stauffer, Hartmann & Barrado y Navascues 1995).

The modelling results show that solid dust grains are unable to fit the observed SED and disc size (Fig. 2). However, using a porosity of p = 0.5 provides a good fit to the SED. The icy model (p = 0.5, q_{ice} = 1.0) is a worse fit than the solid-grain model, so can be rejected. Around 10 μm, there is an additional excess which cannot be accounted for by any model. This is likely to be produced by a hot dust component close to the star. Data in this part of the spectrum have therefore been excluded from the fit, and do not contribute to the total χ² quoted in Table 5.

Detailed modelling of this object has been done previously by Augereau et al. (1999b), and the results here are in good agreement with this work. Augereau et al. made a much more thorough exploration of parameter space, but their overall conclusion was that two dust populations are required: a cool component at 70 au, and a hotter component at about 10 au. Their best-fitting model for the cool dust has amorphous grains with a porosity of p = 0.6 and an ice fraction ice q_{ice} = 0.03. In their analysis, the diameter of the ring was constrained to be 70 au, but the grain porosity, ice fraction and the width of the dust ring were all left as free parameters. As for

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Fomalhaut, our results confirm that the simpler model used here is able to produce similar results to a more detailed model.

Modelling of HR 4796 has also been done by Li & Lunine (2003a), and they were able to fit the entire SED without having a hot dust component, in contrast to the results of Augereau et al. (1999b) and the results presented here. This discrepancy is probably because the model of Li and Lunine contains a large number of grains which are much smaller than the blow-out diameter, and these small grains produce a hot component in the SED even though they are distant from the central star.

6.3 $\epsilon$ Eri

$\epsilon$ Eri is a particularly interesting object, as it is the only cool star (K2V) with a resolved dust disc, all other resolved discs being around A stars. SCUBA images of $\epsilon$ Eri show a distinct ring, which is approximately face on and has a radius of 60 au (Greaves et al. 1998).

In modelling the dust disc of $\epsilon$ Eri, a problem arises due to the low luminosity of the star. Our model for the dust size distribution assumes that radiation pressure will remove the smallest dust grains. However, in the case of $\epsilon$ Eri the radiation pressure is not sufficient to blow dust grains out of the system when porus dust grains are used (Fig. 3). In this situation, it is not clear what limits the size of the smallest dust grains. As a first step, we made the ad hoc assumption that when porous grains were used, the small size cut-off is set at the grain size where $\beta$ is greatest, i.e. where the radiation force is most significant compared to the gravitational force. Modelling using this assumption produced a very interesting result: all of the models predict too much flux in the mid-IR, and too little in the submillimetre (Fig. 4). This means that our models have too many small (and therefore hot) dust grains. This is an unexpected result, as there is no obvious mechanism for removing the small grains. By varying the minimum size cut-off explicitly, an excellent fit is possible, but only if the cut-off size is set to 3.5 $\mu$m and the $p = 0$ model is used, as shown in Fig. 5. It is also possible to obtain a good fit using porous grains, but only if the minimum size cut-off is set to around 300 $\mu$m (Fig. 6). This model does not predict the observed excess at 25 $\mu$m, but this flux could come from an...
It therefore seems that the disc around $\epsilon$ Eri contains few grains smaller than about 3 $\mu$m, and radiation pressure from the star cannot explain this deficit. Possible causes for this discrepancy are discussed in Section 7.

Recently, detailed modelling of $\epsilon$ Eri has been presented by Li, Lunine & Bendo (2003) who modelled the SED and SCUBA image using a porous dust model ($p = 0.9$, $q_{\text{loc}} = 0.0$), and were able to get an excellent fit. With this in mind, our results seem somewhat surprising, as they favour solid rather than porous grains, and fail to produce an acceptable fit at all unless grains with diameter smaller than 3.5 $\mu$m are excluded. The discrepancy arises because of several differences in the assumptions made within the two models. The most important difference is that Li et al. (2003) set a maximum grain size cut-off at a diameter of 2 cm, whereas in our modelling the maximum grain size is set to be 10 m. If the collisional cascade model is true, then the real size distribution will extend up to very large bodies (i.e. kilometre scale and bigger), but the limit of 10 m is chosen because bodies of this size and larger make a negligible contribution to the submillimetre flux (i.e. the longest-wavelength data included in our fits), and so can be safely excluded from the model. This is not true of 2-cm bodies, as grains of around this size can make a very significant contribution to the flux at 850 $\mu$m. Similarly, Li et al. (2003) set an a priori limit on the minimum grain diameter at 2 $\mu$m; our finding that we must remove grains smaller than 3.5 $\mu$m is therefore in reasonable agreement with this (the remaining discrepancy is due to the fact that Li et al. (2003) allow the slope of the size distribution to be a free parameter, whereas in the models where we modified $D_{\text{min}}$, $q$ was fixed to be 11/6). Finally, Li et al. (2003) have a different spatial dust distribution, with a peak at 55 au and FWHM of 30 au, compared with the infinitely thin ring at 60 au used in our model. The broad spatial distribution has not been considered here as it would make our SED fit worse. Because Li et al. (2003) set tight limits on the size distribution, the dust SED becomes quite sharply peaked, and a broad spatial distribution is needed to make the dust SED wide enough to fit all the points.
Conversely, in our model the broad size distribution means that the model SED is already too wide, so a broad spatial distribution would only make things worse. Given the low signal-to-noise ratio of the SCUBA image, a direct measurement of the width of the dust ring is not possible.

Dent et al. (2000) also modelled the ϵ Eri data, and were able to fit the SED using a modified black-body. The fitted parameters indicated that the disc must contain large grains (∼30 µm), but this type of modelling does not constrain the composition or porosity of the dust grains.

6.4 Vega

The original estimate for the size of Vega was made by Aumann et al. (1984), who analysed special pointed observations made with IRAS after the discovery of a far-IR excess. The estimated diameter was 23 arcsec at 60 µm (corresponding to a radius of 90 au). Subsequently, these data were reanalysed, giving a larger diameter of 35 ± 5 arcsec (135 au) (van der Bliek, Prusti & Waters 1994, and references therein). This discrepancy is attributed to the fact the Aumann et al. did not account for the photospheric emission at 60 µm, and hence underestimated the extent of the excess emission. However, submillimetre observations made with SCUBA on the JCMT indicate a diameter of 24 ± 3 arcsec (Holland et al. 1998), similar to the original estimate from the IRAS data. At millimetre wavelengths, aperture synthesis imaging has been done using the Plateau de Bure interferometer (Wilner et al. 2002) and Owens Valley Radio Observatory (Koerner, Sargent & Oストroff 2001). Both of these observations suggested that the Vega disc is very clumpy, and found bright clumps at a distance of 9 arcsec (Plateau de Bure) and 12 arcsec (Owens Valley) from the central star. This could indicate a disc radius as small as 70 au.

Given these observations, it is not obvious what the true size of the disc is, and so we were unable to fix this parameter in our model fits. Instead, we fitted different grain models with disc size as a free parameter. With this approach we find that all of the dust grain models fit equally well (Fig. 8), but predict very different disc sizes. The porous-grain models both have a fitted radius much larger than any of the observations, with the p = 0.5, q_ice = 0.0 model suggesting a radius of 191 ± 16 au, and the p = 0.9, q_ice = 0.0 model giving 237 ± 21 au. These models can therefore be rejected. However, the solid-grain model (p = 0.0) gives a radius of 120 ± 13 au, and the icy p = 0.5, q_ice = 1.0 model gives 92 ± 8 au, both of which are compatible with the observations. Without more detailed analysis of the structure observed in the disc, it is impossible to distinguish between these two options.

There is a small additional excess at 25 µm (∼2 Jy), which none of the models account for. This could either be due to an additional warm dust component similar to that found for HR 4796, or because the spatial distribution is broad, with dust at a range of distances from the star.

6.5 β Pic

β Pic is the most extensively studied Vega-excess star, with observations in scattered light, mid-IR, far-IR and submillimetre. The system is not a ring, but a disc with dust at a variety of distances from the star. The system has been modelled in detail by Li & Greenberg (1998a), and our simpler model is not adequate to deal with the extended spatial structure of the disc. However, we have included β Pic here in order to show the consequences when our model is applied to objects where the dust is not contained within a ring. The ring morphology is one of the key assumptions of our model, so it is extremely important that we can determine whether or not this is true for unresolved objects.

To fit the SED, we used the same approach taken for Vega, i.e. we left the ring radius as a free parameter, and fitted each dust composition to the SED. The modelling shows that it is not possible to fit the observed SED with any single model regardless of what dust composition is chosen (Fig. 9). This is a helpful result, in that it shows that we are able to distinguish between a disc and a ring morphology purely from the SED. However, this modelling reveals little else about the composition and size distribution of dust grains in β Pic.

6.6 HD 141569

HD 141569 has a resolved circumstellar disc, first directly detected in near-IR scattered light images (Augereau et al. 1999a; Weinberger et al. 1999), and subsequently resolved in mid-IR thermal emission (Fisher et al. 2000; Mouillet et al. 2001; Marsh et al. 2002). Most recently, the disc has been observed with the ACS coronagraph (Clampin et al. 2002), revealing that the structure observed in the
disc is probably caused by a tidal interaction with a bound binary system at a projected distance of around 1000 au. The age of the system has been estimated to be $5 \pm 3$ Myr (Weinberger et al. 2000), making it one of the youngest stars in our sample. However, despite its youth the disc appears to be in a collisional cascade, as modelling shows that it contains small dust grains which must leave the system on a very short time-scale (Fisher et al. 2000).

The mid-IR imaging shows that the overall size of the disc is around 100 au, but the emission is produced at a range of distances from the star from 20 au outwards (Marsh et al. 2002). This is also apparent from our SED modelling, as no model can simultaneously fit all the data (Fig. 10). When only the long-wavelength points are fitted (i.e. only the cooler, outer parts of the disc), the fitted radius is about 50 au if solid ($p = 0$) or icy ($p = 0.5, q_{\text{ice}} = 1.0$) grains are used, but 114 au for porous grains ($p = 0.9, q_{\text{ice}} = 0.0$). This indicates that the thermal emission is probably produced by porous grains, in agreement with the modelling done by Li & Lunine (2003b).

6.7 HD 109085

HD 109085 is clearly detected in the submillimetre, indicating that the IRAS association is real. However, no model can simultaneously fit all of the data (Fig. 11). This indicates that there must be dust at a variety of distances from the star, as is the case for $\beta$ Pic and HD 141569. For our fitted model, the IRAS 12- and 25-µm points have not been included, so the fitted radius reflects the size of the coolest parts of the disc, i.e. the overall extent of the disc. This gives a result of 180 au, which at a distance of 18.2 pc gives an angular radius of 9.9 arcsec. This is more extended than the SCUBA beam, so our flux estimate is probably smaller that the true flux by a factor of $\sim 2$ (Table 3). Given the size and brightness of the disc, it should be possible to map HD 109085 fully with SCUBA, and such observations are currently being performed (Wyatt et al. in preparation).

6.8 HD 38393

HD 38393 is extremely faint in the submillimetre, and is only detected at the 2.4 σ level. The modelling produces a good fit to the SED (Fig. 12), but with a disc radius of 200 ± 50 au for solid dust grains. At the distance of HD 38393 (9.0 pc), this corresponds to a radius of 22 arcsec. This would place most of the flux outside the SCUBA beam (even though the extended photometry mode was used), implying that the true flux at 850 µm is much higher than the measured flux. In fact, if this radius is correct we would only detect emission if the source is edge-on. Revising our estimate of the 850-µm flux results in a still larger fitted radius (because a higher submillimetre flux indicates a cooler disc), and so does not resolve this problem. Nor does choosing a different dust composition, as porous grains tend to be warmer than solid grains, and so also increase the estimated disc size.

Given the low significance of the detection, it is possible that the 850-µm detection is either spurious, or caused by a background galaxy. Using source counts of galaxies detected in blank fields (e.g. fig. 11 in Scott et al. 2002), we find there is a 6 per cent probability that a 2.4 mJy background source will fall into the beam of SCUBA in extended photometry mode (which is sensitive over a 300-arcsec$^2$ area). Habing et al. (2001) also concluded that their 170-µm detection is likely to be due to a background galaxy, given the low flux and the galaxy number counts at that wavelength. However, an alternative explanation is that the estimate of the disc size is wrong: the difficulty fitting the SED of $\epsilon$ Eri may indicate that our model
is generally unreliable for cool stars, and hence the true size of the disc could be smaller than 200 au. This would mean that the disc is deficient in small grains compared with our model.

6.9 σ Boo

Excess submillimetre emission from σ Boo was detected at the 3.6σ level, with a flux of 6.7 mJy. However, the best-fitting model (Fig. 13) gives a disc radius of 320 ± 90 au, which corresponds to an angular radius of 20 arcsec, implying that most of the 850-μm flux would be outside the SCUBA beam even in extended photometry mode. In addition, the best-fitting model predicts a much lower 850-μm flux than the observed value. As is the case for HD 38393, there is no model which is consistent with both the SED and the spatial constraints given by the SCUBA beam size. The problem is unlikely to be caused by errors in the far-IR data: the IRAS and ISO results are entirely consistent, and the ISO 170-μm observation has a beam radius of about 45 arcsec, so all the flux would be detected with ISO, even if the disc really is very large.

Habing et al. (2001) considered the possibility that their ISO detection at 60 and 170 μm was due to a background galaxy. They concluded that the excess was probably real, but could not rule out contamination by a background source. A background galaxy with a flux of 6.7 mJy is unlikely to fall into the SCUBA beam by chance alone (1 per cent probability), but as σ Boo was selected on the basis of a far-IR excess, contamination by a background source becomes more likely. The alternative explanation is that σ Boo is deficient in small grains, which would reconcile the modelling results with the SCUBA beam size.

6.10 HD 48682

HD 48682 is a quoted as visual binary in the Washington double-star catalogue with a separation of 34 arcsec. However the two stars cannot be physically associated due to their differing proper motions, and it appears that HD 48682B is in fact a background object. Given that the separation of the two components is similar to the IRAS beam size, it is not obvious whether the photosphere of the secondary will contribute to the IRAS fluxes or not. The IRAS beam is different at each wavelength, as the diffraction limit is much smaller at 12 μm than it is at 100 μm. This means that the secondary photosphere may only contribute to the measured fluxes at longer wavelengths. In addition, it is very difficult to estimate the brightness of the secondary at IRAS wavelengths, because the star is most likely an M star and only optical photometry is available. A small uncertainty in the effective temperature therefore causes a large error in the estimated mid-IR flux. A K-band image would resolve this problem, but unfortunately the secondary star is saturated on 2MASS images, so a dedicated observation would be required. Aumann & Probst (1991) made ground-based observations of HD 48682 at 10 μm, and concluded that the 12-μm excess comes from >6 arcsec from the primary and is consistent with the flux from the secondary, but that the secondary photosphere cannot account for the large 60-μm excess. Our detection with SCUBA confirms that the 60-μm IRAS excess is associated with the primary and not the secondary, but the source of the 12- and 25-μm excess is not clear.

Fig. 14 shows the SED of HD 48682, and the best-fitting model. The modelling has been done in two ways, with and without the secondary included in the photosphere subtraction (assuming a spectral type M0). At 12 μm, the IRAS flux is more than the photosphere of the primary, which could either be due to circumprimary emission at >6 arcsec, or flux from the secondary. At 25 μm, the IRAS flux is more than the combined flux from primary and secondary, indicating that there is definitely emission by dust at this wavelength. There is a large excess at 60 μm, and the secondary photosphere could only make a small contribution even if it is within the beam. The modelling results are better if the secondary is included in the photosphere subtraction (reduced χ² = 3.1, versus 7.0 if the secondary is not included). If the secondary is not included in the subtraction, the estimated radius is 71 ± 15 au, whereas if the secondary is included, the estimated radius is 110 ± 21 au. If the larger value is true, the projected radius would be 6.7 arcsec, so the disc could be marginally resolved with SCUBA mapping. The shape of the fitted model indicates that there would be only a small excess at 18 μm, so resolved ground-based imaging would be difficult.

6.11 HD 207129

HD 207129 is not detected in our reduction of archived SCUBA measurements, but because there are ISO measurements at 170 μm...
a model fit is possible, and the SCUBA upper limit also helps to constrain this fit. The SED and model fit are shown in Fig. 15. The fitted size of the disc is 260 ± 50 au, which corresponds to an angular radius of 17 arcsec. Since this is larger than the SCUBA beam a significant fraction of the flux would not have been detected, and the quoted upper limit on the 850-µm flux may actually be lower than the true flux. HD 207129 was observed in both photometry mode and map mode, and the quoted upper limit of <0.018 Jy is based on both sets of measurements. If just the mapping data are used, then an integrated flux over a 20-arcsec-radius aperture can be calculated. This method gives a flux <0.05 Jy (3σ).

7 DISCUSSION

The most striking result of our modelling is that there is a large diversity in dust grain compositions between different discs. A simple explanation for this result is that dust grain composition may vary with age. The modelling of HD 141569 and HR 4796 (age 5 and 8 Myr, respectively) indicates high-porosity grains (p = 0.9), as does the previous modelling of β Pic (age 20 Myr) done by Li & Greenberg (1998a). However, solid grains are indicated for Fomalhaut and Vega (ages 150 and 350 Myr). It may be that the older stars have less-porous grains because the collisional cascade has reprocessed the initially fluffy grains into a more solid form. An alternative explanation is that the change in porosity is due to the effects of stellar radiation on the dust, as suggested to explain the differences between the porosity of long- and short-period comets (Mukai & Fechtig 1983; Li & Greenberg 1998b). Clearly, a larger sample of resolved discs is required to confirm this trend.

The failure of our basic model to fit the SED of ε Eri is extremely interesting, and it is important to determine what is causing the poor fit. There are essentially two possibilities: either there is an unknown physical effect which is modifying the size distribution in the particular case of ε Eri, or else the size distribution model we have assumed is intrinsically wrong.

ε Eri is known to have a planet (Hatzes et al. 2000), with a semimajor axis of 3.4 au and a mass of around two Jupiter masses (assuming an inclination of 25° as measured by Greaves et al. 1998). This planet is unlikely to affect the dust size distribution at 60 au, because of its small orbital radius. However, a planet with a large semimajor axis has been inferred from the existence of clumps within the dust disc (Quillen & Thorndike 2002). If this planet is real, then dynamical effects are clearly very important in shaping the disc, and this would undoubtedly affect the size distribution of the dust.

The alternative explanation is that the discrepancy is not due to an external influence, but that a more accurate treatment of the dust grain size distribution in a collisional cascade is needed to account for the SED. More detailed size distribution models allow the grain strength to vary with grain size, and account for the effects of removing small grains on the overall size distribution (Campo Bagatini et al. 1994; Durda & Dermott 1997). For β Pic, extensive numerical models of this type have been produced, both for the inner disc (Thébault, Augereau & Beust 2003) and for the outer disc (Krivov, Mann & Krivova 2000). Both of these studies show significant deviation from the theoretical size distribution used in this paper. This suggests that a more rigorous treatment of the collisional cascade in ε Eri would also give a significantly different size distribution. However, it is not obvious that this would produce a better fit to the SED (i.e. that the new size distribution would have few grains smaller than 3 µm). In fact, according to Campo Bagatini et al. (1994) we should expect an enhancement of grains just above the blow-out radius as they are less likely to be destroyed by collisions, which would make the problem worse. Conversely, the modelling of the outer disc of β Pic by Krivov et al. (2000) suggests a reduction in the number of grains just above the blow-out limit, because they are destroyed by small, fast-moving grains as they are ejected from the system by radiation pressure. However, as the stellar luminosity is much lower for ε Eri, this mechanism is likely to be less important. Only detailed modelling specific to the dust disc of ε Eri can answer this question.

The new submillimetre data significantly expand the sample of true Vega-excess stars detected at this wavelength. Regardless of the dust properties, we are able to distinguish between a disc morphology and a ring morphology. Out of the five new objects, only HD 109085 is disc-like, indicating that this type is less common than the ring-like structure observed around Fomalhaut and ε Eri.

One of the main aims of this work was to determine the size of an unresolved disc from just its SED. However, the modelling of resolved targets has shown that this may not be possible. The large diversity in dust properties for the resolved discs mean that we cannot make a reliable assumption as to the composition of the grains in an unresolved disc. In addition, the poor fit to the SED of ε Eri shows that the model may not in general contain all of the physics necessary to account for the observations. Our estimates of the disc size are based on assumption that the dust grains are solid (as for Fomalhaut), but if the grain properties are different, then the size estimates will be incorrect.

Future progress in this field depends on spatially resolving discs, as this allows a direct measure of disc size and thus measurements of the dust composition. Our results indicate that there are probably a few more targets that can be resolved using SCUBA, given sufficient integration time. Also, ground-based mid-IR observations have the ability to resolve some discs. However, large numbers of resolved discs may have to wait until SIRTF and SOFIA become available.

8 CONCLUSION

We have presented new observations and modelling of Vega-excess discs with submillimetre data. Our observations expand the sample of Vega-excess stars detected in the submillimetre from five to 10,
with a further four objects which were not detected but have useful upper limits. We have fitted the observed SEDs with models based on realistic dust grain composition and size distribution. We find that dust grain composition varies significantly between different objects, with younger discs having more porous grains. For ε Eri, our model fails to fit the data unless there are fewer small grains in the system than expected from a collisional cascade. This discrepancy may be due to an inadequacy in our model of the size distribution, or the result of an external influence such as a planet. For the unresolved targets, disc size is estimated assuming solid dust grains, but given these size estimates may not be reliable.

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