Optical, infrared and millimetre-wave properties of Vega-like systems – III. Models with thermally spiking grains

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ABSTRACT
Vega-like stars are main-sequence stars that exhibit excess IR emission due to circumstellar dust grains which are probably distributed in discs. We have recently published an observational data base for a large sample of candidate Vega-like systems, comprising optical, near-IR and mm/submm-wave photometry, and mid-IR spectra. In a previous paper we presented radiative transfer models of eight sources from our sample that had low fractional excess luminosities. Here we present models of a further eight sources, all with large fractional excess luminosities dominated by excess emission at near-IR wavelengths. It was found that no single distribution of dust grains at thermal equilibrium in a disc could simultaneously match the excess emission at near-IR and longer wavelengths. We attempted to model the near-IR emission as due to thermally spiking small grains, which can temporarily attain the high temperatures required to produce excess near-IR emission. A near-IR spectrum of SAO 186777 shows the 3.3-μm UIR emission band, confirming our earlier detection of UIR emission at longer wavelengths, and suggesting that small carbonaceous particles are responsible for some of the near-IR emission. The thermally spiking models were only partially successful and many of the sources required the presence of grains emitting in thermal equilibrium at ~1000–1500 K. These grains must either be located very close to the stars (<1 au), or else be powered by accretion luminosity.

Calculations of the optical depths of the model discs suggest the discs are optically thick at visual wavelengths; optically thick modelling of these sources is desirable. The discs are optically thin at mm wavelengths, allowing us to confirm the presence of large grains in the discs. The stars presented in this paper may well be younger than the prototype Vega-like stars.

Key words: circumstellar matter – planetary systems – infrared: stars.

1 INTRODUCTION
Vega-excess, or Vega-like, systems are main-sequence stars that display substantial far-IR excess emission. The best known Vega-excess stars are α Lyn itself and β Pic. The excess emission is ascribed to circumstellar dust grains orbiting in a disc or ring structure (see e.g. Aumann et al. 1984).

A number of searches of the IRAS catalogues have found other candidate Vega-like stars (e.g. Aumann 1985; Walker & Wolkencroft 1988). Comprehensive reviews of the Vega-excess phenomenon and its relation to the formation of extra-solar planets can be found in Backman & Paresce (1993) and Ferlet & Vidal-Madjar (1994).

We have recently published the results of a major observational survey of a sample of some 24 Vega-like stars, including UBVRI optical photometry, near-IR photometry, mid-IR spectroscopy and mm/submm-wave photometry (Sylvester et al. 1996, henceforth Paper I). We presented models of a subset of our sample (Sylvester & Skinner 1996, henceforth Paper II), comprising the stars with no detectable near-IR (1–5 μm) excess emission. The models were produced using a radiative transfer code based on that used by Skinner, Barlow & Justtanont (1992) to model SAO 179815 (HD 98800) and similar to that used by Skinner et al. (1995) to model SAO 26804. In this paper, we present models of a another subset of stars from Paper I. These stars are distinguished by their excess emission at near-IR wavelengths, and the large fractional excess luminosity of the dust. Most of them show Hα emission and other spectroscopic evidence of youth (Dunkin, Barlow & Ryan 1997b); they may be transition objects between the Herbig Ae/Be or T Tauri phases and established main-sequence stars (Waelkens, Bogacrt & Waters 1994; Dunkin et al. 1997b).
2 THERMAL EQUILIBRIUM MODELLING

The modelling code described in Paper II, to which the reader is referred for details, was used to model all the stars in this paper. Briefly, it uses optically thin radiative transfer methods to calculate the temperature of grains distributed in a disc around the star, which is itself modelled using a Kurucz (1991) model atmosphere. The spectral energy distribution of the emission from the star-disc system is then calculated. A wide range of grain sizes is used, with a power-law size distribution; the variation of dust density within the disc with distance from the star was also treated as a power law.

The central star was defined by its effective temperature, surface gravity and radius (all determined from the spectral type), and its distance (determined from optical photometry, adopting the absolute magnitude calibration of Schmidt-Kaler 1982). The dust grains were described by their composition, their maximum and minimum sizes (\(a_{\text{min}}, a_{\text{max}}\)), and the power-law index, \(\gamma\), for the size distribution. For all the models, \(a_{\text{min}}\) was set to 50 \(\AA\).

The disc structure was described by its inner and outer radii (\(R_n, R_o\)), the density-distribution index, \(\beta\), and the total mass of the disc, \(M_{\text{disc}}\). The dust temperature was calculated as a function of grain size, composition and distance from the central star, by applying the condition of radiative equilibrium.

Output from the model was produced in two forms: spectral energy distributions (SEDs), and simulated fluxes in the four IRAS bands and in two mm-wave bands for comparison with James Clerk Maxwell Telescope (JCMT) observations. For a detailed description of how the various model parameters affect the predicted SED, we refer the reader to Paper II.

3 MODELLING WITH SMALL GRAINS

As shown in Paper I, several Vega-excess stars display excess near-IR emission, e.g. SAO 77144 (HD 35187) and SAO 183986 (HD 143006). Inspection of the spectral energy distributions suggests that this excess is not merely the short-wavelength extension of the excess seen at mid- and far-IR wavelengths, but rather that there is a double-peaked structure to the overall excess energy distribution.

This may imply that there is more than one distinct spatial distribution of dust, and/or that there is more than one type of grain behaviour taking place. The first scenario, that there are two or more populations of grains in thermal equilibrium, runs into the problem that the dust temperatures required to produce a near-IR excess, approximately 1500 K, are higher than the sublimation temperature of circumstellar dust (approximately 1000 K). In other words, it would be impossible for dust to survive at the required temperatures for an extended period of time. Even if the evaporating dust was continuously being replenished, for instance by dust falling in from the cool outer regions of the disc, it may still be destroyed before reaching a temperature of 1500 K.

We therefore consider the second possibility – that there is another physical process at work to produce the observed near-IR excesses.

3.1 The small-grain hypothesis

Such a process was suggested by Greenberg (1968), who pointed out that the energy gained by a small grain upon absorption of a single photon could be comparable to the energy content of the grain. The grain would therefore not be in thermal equilibrium, but would undergo temperature fluctuations. Thermally spiking small grains were proposed by Sellgren, Werner & Dinerstein (1983) to explain observations of reflection nebulae which showed near-IR continuum and unidentified-infrared (UIR)-band emission. These small grains (radius ~10 \(\AA\)) have a very low heat capacity, and so can be heated to temperatures of the order of 1000 K by the absorption of a single UV photon.

Small grains have been used to model the emission from the planetary nebula Abell 30, and gave a good fit to the near-IR observations (Borkowski et al. 1994). Hartmann, Kenyon & Calvet (1993) and Natta, Prusti & Kügel (1993a) suggested that small grains could be responsible for a significant fraction of the near-IR excess emission of Herbig Ae/Be stars.

Several of the Vega-like stars in our sample show mid-IR UIR-band emission (Paper I), which is thought to be due to small carbonaceous particles, such as polycyclic aromatic hydrocarbons (PAHs). This lends weight to the suggestion that thermally spiking grains are present in Vega-like discs. A 3-\(\mu\)m spectrum of SAO 186777 obtained with the CGS4 spectrometer at a UKIRT Service observation is presented in Fig. 1. The spectrum shows emission in the 3.3-\(\mu\)m band, while only 25 per cent of the underlying continuum is due to the photospheric radiation field of the A5Ve star.

The 3.3- and 11.3-\(\mu\)m UIR bands are both thought to arise from the C–H bond in PAHs; this allows the temperature of the emitting material to be estimated from the band strengths (de Meijer, d'Hendecourt & Geballe 1987). We find an integrated flux of \((4.4 \pm 0.6) \times 10^{-15}\) W m\(^{-2}\) in the 3.3-\(\mu\)m band and \((1.0 \pm 0.1) \times 10^{-14}\) W m\(^{-2}\) in the 11.3-\(\mu\)m band (having scaled the CGS3 10-\(\mu\)m spectrum to the IRAS 12-\(\mu\)m flux – see Paper I).

This gives a flux ratio \(I(11.3)/I(3.3) = 2.4\), which is similar to that found for the Red Rectangle (Léger & d'Hendecourt 1987). Using fig. 3 of de Meijer et al. (1987), this ratio gives a temperature of 1000 ± 80 K. This is the average temperature of the PAH molecules as they cool after a thermal spike, and is roughly 2/3 of their peak temperature. Coulson & Walther (1995) performed similar calculations for SAO 206462, and deduced a temperature of 515 ± 25 K. The higher temperature for SAO 186777 may be due to the ‘harder’ radiation field, as it has an earlier spectral type. From these results it is clear that there is a thermally spiking component of...
the dust around these Vega-excess stars, which reaches temperatures of at least several hundred K.

3.2 Calculating the temperature distribution

The thermal behaviour of a small grain in a radiation field can be described by its probability distribution function \( P(T) \), where \( P(T) \, dT \) is the probability of finding the grain in the temperature interval \( (T, T + dT) \). To determine this function, the method of Guhathakurta & Draine (1989, henceforth GD89) was used, whereby the range of possible temperatures is divided into a number of discrete bins, and the probability of a grain occupying each bin is calculated.

For the present work, typically 300 bins were used: experimentation showed that this was sufficient to avoid any problems due to having too coarse a spacing, and gave results that showed negligible differences compared with those obtained using a much larger number of bins (several thousand). Using a small number of bins gives considerable savings in the amount of computer time required.

Following GD89, we treated the heating due to long-wavelength (\( \lambda > 1 \) mm) radiation as continuous, rather than discrete photon interactions, to ensure non-zero minimum grain temperatures. Typical values of \( T_{\text{min}} \) were found to be \( \approx 0.5 \) K.

The temperature for the highest enthalpy bin, \( T_{\text{max}} \), was usually set to 2000 K, as it was found that the probability of a grain being above this temperature was normally extremely small. Also, grains much hotter than 2000 K will lose energy by sublimation rather than by radiative cooling (GD89; Voit 1991) and so will not contribute significantly to the model emission.

If the grains are near thermal equilibrium (i.e. multiphoton absorption is important), grains at low temperatures make a negligible contribution to the emission, because the probability of a grain being at a low temperature is very small, and because cool grains emit very weakly. In order not to ‘waste’ enthalpy bins on these unimportant temperatures, a third temperature parameter, \( T_{\text{base}} \), was introduced such that the temperature interval \( T_{\text{min}} < T < T_{\text{base}} \) is spanned by only 10 equally spaced enthalpy bins, allowing the bins in the range \( T_{\text{base}} < T < T_{\text{max}} \) to be more closely spaced (equally spaced bins were also used in this regime).

To determine the probability distribution function of the grain, GD89 defined a set of probabilities, \( P_k(t) \), as the probability of the grain being in the \( k \)th enthalpy bin at a time \( t \). As its temperature fluctuates, a grain will move among the bins. An ensemble of identical small grains in a static radiation field will exist in a dynamical equilibrium where the number of grains in a particular bin remains constant with time, although each individual grain is making transitions among the bins as it absorbs photons and subsequently cools down. Steady-state probabilities, \( P_k^{\text{SS}} \), can therefore be defined.

The grain cooling process is treated as continuous – discrete cooling events, where a grain can go from one state to a cooler one without passing through all the intermediate states, are not allowed in the GD89 treatment. This greatly simplifies the problem of solving the equations to determine the steady-state probabilities. Siebenmorgen, Krügel & Mathis (1992) pointed out that for real grains, discrete cooling events could occur, and suggested that this would give rise to more far-IR and submm emission than predicted by the GD89 method.

For the extreme example given by Siebenmorgen et al. of a 5-Å grain 0.16 pc from a B1V star, allowing discrete cooling events increases the submm flux by a factor of approximately 20.

However, for Vega-excess stars, such a discrepancy would make no appreciable difference to the total submm fluxes, since the equilibrium emission of ‘normal’ large grains is typically 2–3 orders of magnitude stronger than the small-grain emission at submm wavelengths.

GD89 also considered discrete heating due to collisions between the grain and other particles, but collisional heating was ignored for the present work.

3.3 Output

The results from the model were recorded in two forms – a probability distribution function (pdf) and a spectral energy distribution. The pdf was found by converting the discrete steady-state probabilities into values of the continuous function \( P(T) \). This was achieved by dividing the probability of a grain being in a bin by the temperature interval covered by the bin, \( \Delta T_k \). The quotient obtained is a good approximation to the value of the pdf at the temperature \( T_k \).

Since a grain is required to be in one or other of the bins, the value of the pdf is zero for \( T < T_{\text{min}} \) and for \( T > T_{\text{max}} \). Tests using a model of a B3V star gave good agreement with the results of GD89.

The spectral energy distribution was determined by calculating the spectrum expected from a grain at the temperature of each bin, and then adding all \( N \) such contributions together, weighted by their respective probabilities:

\[
S_{\lambda, \text{out}} \approx Q_{\lambda, \text{abs}}(\lambda) \sum_{i=1}^{N} P_{i}^{\text{SS}} B_{i}(T_i),
\]

where \( B_i(T_i) \) is the Planck function and \( T_i \) is the temperature of the \( i \)th bin. The absorption (and hence emission) efficiency \( Q_{\lambda, \text{abs}} \) and the probability distribution are functions of grain size, but for the present modelling, only a single size of small grain was used in any given model, rather than a size distribution.

4 SYSTEMS SELECTED FOR MODELLING

The Vega-like systems that we model in this paper are all taken from the sample that was presented in Paper I, and are distinguished by having substantial near-IR excess emission. In total, eight stars are modelled in this paper.

Table 1 lists the stars to be modelled in this paper, and summarizes their observational properties, as discussed in detail in Paper I. Listed are spectral type, \( V \)-band magnitude, and fractional excess luminosity, \( L_{\text{ex}}/L_* \), which is the ratio of the luminosity of the dust disc to that of the central star. For most of the stars in the present paper, \( L_{\text{ex}}/L_* \) is greater than 1/4, the maximum for a physically thin disc, implying that the discs must be substantially flared, or even accompanied by spherical envelopes. Accretion of matter through a disc can add extra IR luminosity; however, in the present models we only consider the reprocessing of starlight.

5 MODELLING PROCEDURE

The modelling technique treats the discs as being optically thin to the stellar radiation powering their emission: for the stars with the largest fractional luminosities, this is not likely to be true. Optically thin models do, however, provide a useful approximation to the circumstellar environments of Vega-excess stars, in the absence of more elaborate techniques.

The procedure for combining equilibrium and small-grain models for stars with near-IR excess emission was to use the equilibrium disc model first, and fit the mid-IR to mm-wave data.
All models that gave good agreement with the mid- and far-IR observations were found to make negligible contributions to the near-IR flux, which allowed the two modelling techniques to be used nearly independently.

Having obtained a well-fitting disc model, small-grain models were computed, with the grains situated at the inner radius found for the disc models. The required mass of small grains was determined by fitting the near-IR excess fluxes. The emission from the small grains was then simply added to the fluxes from the disc model, which included the photospheric contribution. Sometimes the non-zero flux from the small grains in the mid-IR caused the fit to the CGS3 spectrum to deteriorate; a slight increase in the inner radius of the disc model generally sufficed to decrease the disc model’s contribution at 10 µm, and allowed the fit to be recovered.

The radii of the small grains were usually set to 3 or 5 Å. The smaller a grain is, the more likely it will be to undergo temperature spiking; these sizes were chosen to maximize the spiking, while retaining enough atoms in the grain for them plausibly to emit near-IR continuum radiation.

If it was found that thermally spiking small grains gave unsatisfactory fits to the near-IR excess, the distance between the small grains and the star was reduced until the emission from the grains (now approximately in thermal equilibrium) matched the near-IR excess spectral energy distribution. This provided useful measures of the grain temperature characterizing the near-IR excess, and lower limits on the amount of mass required to produce such an excess. The mass lower limits and dust temperatures are valid irrespective of the mechanism that is actually heating the grains – thermal spiking by excess UV photons, equilibrium heating of grains close to the star, or even some process intrinsic to the disc, such as collisional heating.

The disc outer radii were usually set to 10 arcsec, corresponding to the approximate size of the JCMT beam. If a larger value was used, only the flux arising in the inner 20 arcsec (diameter) was included for the tabulated values of the predicted mm-wave fluxes, to allow comparison with the JCMT measurements.

The equilibrium models are labelled with a letter followed by two numbers. The letter refers to the type of dust material used: M for astronomical silicate, C for amorphous carbon (AC), and B for a blend of silicate and carbon. The two numbers refer to γ, the index of the power-law grain size distribution $N(a) = a^{-\gamma}$, and β, the power-law index for the density distribution, $n(R) = R^{-\beta+1}dR$ (see Paper II for details). Decimal points and minus signs are symbolized with p and m respectively. Suffixes a, b, etc. could be used to distinguish between models with the same values of γ and β.

### 6 RESULTS

#### 6.1 SAO 77144 (HD 35187)

SAO 77144 is listed in the Hipparcos Input Catalogue (Turon et al. 1992) as a double star. The two components are separated by 1.2 arcsec, and have equal $V$ magnitudes. For the purposes of modelling this system, it was assumed that the two component stars were identical, but that the grains were heated by only one of them. The results of modelling SAO 77144 are summarized in Table 2.

A grid of pure silicate models was produced (models M22–M2p50p7). Values of inner radius and disc mass were chosen to obtain a good fit at 25 and 60 µm. As can be seen in Paper I, there is some discrepancy between the IRAS 12-µm flux and the CGS3 spectrum of this source. Modelling using a 5.5-arcsec aperture showed that the discrepancy was not due to beam size effects. We assume that the absolute flux calibration of the CGS3 spectrum was in error; the CGS3 spectrum plotted in Fig. 2 has been scaled up by 1.45 to make it consistent with the IRAS 12-µm flux.

A number of equilibrium grain models were run using a blend of 75 per cent silicate grains and 25 per cent amorphous carbon grains (models B22–B31). Table 2 summarizes the fit of these models to the 12 µm to 1.1 mm spectrum of SAO 77144. Model M2p50p7 gives a good fit to the observations, and is plotted in Fig. 2.

The near-IR excess emission of SAO 77144 was modelled using the small-grain code. Small (3-Å radius) silicate grains at 3.3 au from the star were found to be out of thermal equilibrium, and gave a good fit to the near-IR excess photometry. However, they produced a strong silicate emission feature, far in excess of the observed silicate feature in the CGS3 spectrum.

A radius grains of AC gave a good fit to the near-IR photometry without giving rise to spectral features. Combining the two materials, it was found that silicates could form up to approximately 10 per cent of the small-grain population before giving rise to too strong a silicate feature. A mass of $1.2 \times 10^{-5} M_{\text{Earth}}$ of small AC grains at 3.3 au was needed to provide the observed amount of near-IR flux.

Grains of radius 3 Å (the largest that show significant departures from thermal equilibrium) contain approximately 30 atoms, which
Table 2. Models for SAO 77144 (HD 35187).

<table>
<thead>
<tr>
<th>Model</th>
<th>$\gamma$</th>
<th>$\beta$</th>
<th>$R_m$ (au)</th>
<th>$R_{int}$ (au)</th>
<th>$M_{disc}$ ($M_\odot$)</th>
<th>$a_{max}$ (\mu m)</th>
<th>$F_{12}$ (10^{-6} Jy)</th>
<th>$F_{25}$ (10^{-6} Jy)</th>
<th>$F_{60}$ (10^{-6} Jy)</th>
<th>$F_{100}$ (10^{-6} Jy)</th>
<th>$F_{0.8}$ (mJy)</th>
<th>$F_{1.1}$ (mJy)</th>
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<td>2</td>
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<td>1430</td>
<td>9.2 x 10^{-6}</td>
<td>1000</td>
<td>3.6</td>
<td>11.5</td>
<td>8.0</td>
<td>5.0</td>
<td>115</td>
<td>80</td>
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<td>M21</td>
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<td>1</td>
<td>4.0</td>
<td>1430</td>
<td>1.0 x 10^{-4}</td>
<td>1000</td>
<td>5.7</td>
<td>11.4</td>
<td>8.0</td>
<td>4.0</td>
<td>149</td>
<td>74</td>
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<tr>
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<td>2</td>
<td>7.4</td>
<td>1430</td>
<td>2.8 x 10^{-5}</td>
<td>1000</td>
<td>3.7</td>
<td>11.4</td>
<td>8.0</td>
<td>4.0</td>
<td>149</td>
<td>74</td>
</tr>
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<td>1430</td>
<td>2.6 x 10^{-4}</td>
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<td>4.9</td>
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<tr>
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<td>1000</td>
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<td>11.4</td>
<td>8.0</td>
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<td>33</td>
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Figure 2. Results of modelling SAO 77144 (HD 35187). Filled squares: observed fluxes; solid line: model M2p50p7; dotted line: effect of adding small thermally spiking AC grains to M2p50p7.

6.2 SAO 131926 (HD 34282)

This star has no MK spectral type, so the HD classification of AO has been adopted, with luminosity class V assumed. No CGS3 spectrum is available for this source.

The near-IR photometry of SAO 131926 (Paper I) shows strong excess emission, so there is probably a contribution to the flux in the IRAS 12-\mu m band from the material responsible for the short-wave excess. Thus no attempt was made to fit the 12-\mu m point; the inner radius and disc mass were adjusted to give fits at 25 and 60 \mu m.

Figure 3. Detail of the SAO 77144 models in the mid-IR. Error bars: CGS3 spectrum scaled up by a factor of 1.45; large square: IRAS point; solid line: model M2p50p7; dashed line: effect of adding small grains.
Grids of models were run using silicate grains (models M24–M2p81), silicate–AC blend (models B22–B2p72) and AC grains (C21–C10p5). Results are presented in Table 3. The best-fitting model was M2p72, the spectral energy distribution (SED) of which is presented in Fig. 4.

The near-IR excess of SAO 131926 was modelled using the small-grain technique. 3 Å radius grains (silicate or AC) were again found to be thermally spiking, and emitting in the near-IR. The fit is not ideal, with a $\gamma$, $\beta$ flux ratio that is too low. Using larger radius AC grains situated 540 au from the star (roughly the inner radius of the disc models). These grains were found to be close to thermal equilibrium, with peak temperatures of around 400 K for silicate grains caused the fit to deteriorate. In the absence of a CGS3 spectrum, it cannot be determined whether the material is silicaceous or carbonaceous. With the 3 Å radius AC grains situated 1.5 au from the star (roughly the inner radius of the disc models), it was found that slightly 1 Earth mass ($M_{\text{Earth}}$) of small grains was required to produce sufficient near-IR flux. This mass is roughly one per cent of the mass of grains in the disc model M2p72. The effect of combining this small-grain model with model M2p72 is illustrated in Fig. 4.

6.3 SAO 183956 (HD 142666)

Van der Veen et al. (1994) detected continuum emission from the A8Ve star SAO 183956 at 0.45, 0.8 and 1.1 mm, and found that the near-IR to mm-wave excess energy distribution could not be successfully modelled with a single dust shell.

The IRAS 12-μm point and the CGS3 10-μm spectrum from Paper I were treated as upper limits for the flux from the thermal equilibrium models, because the material responsible for the near-IR excess could make some contribution to the flux in the 10-μm region.

A grid of silicate models (models M21–M1p51p5: see Table 4) was produced, and one of grain blend models (B31–B11p1). The grid of silicate models shows that well-fitting models lie in a well-defined locus in ($\gamma$, $\beta$) space. Part of the 10-μm silicate feature may be due to small-grain emission, so it is not possible to use the contrast of the silicate feature to determine the value of the power-law size index $\gamma$, which would allow a unique model to be specified. Future high-resolution imaging of the system might allow the spatial distribution of the dust, and hence $\beta$, to be determined with sufficient precision to specify a unique model.

Small-grain models were produced for silicate and AC grains of radius 5 Å, situated 1.5 au from the star (roughly the inner radius of the disc models). These grains were found to be close to thermal equilibrium, with peak temperatures of around 400 K for silicate and 750 K for AC grains.

Grains of radius 3 Å exhibited thermal spiking behaviour, but the resulting spectral energy distribution of the small-grain emission peaked at too long a wavelength to give a good fit to the near-IR excess. A 3 Å radius grain contains only a few dozen atoms; any smaller ‘grain’ would be unlikely to emit the continuum near-IR radiation that is observed. For small-grain emission to be the dominant mechanism causing the near-IR excess, the radiation field of SAO 183956 must therefore be harder than that of the model atmosphere, i.e. excess ultraviolet emission would be required.

Some information can be deduced about the temperature and mass of the material that is responsible for the near-IR excess. This can be achieved by considering grains close enough to the star that they are hot enough to emit strongly in the near-IR.

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Table 4. Models for SAO 183956 (HD 142666).

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<th>Model</th>
<th>$\gamma$</th>
<th>$\beta$</th>
<th>$R_{\text{in}}$ (au)</th>
<th>$R_{\text{out}}$ (au)</th>
<th>$M_{\text{disc}}$ ($M_\odot$)</th>
<th>$a_{\text{max}}$ (\mu m)</th>
<th>$F_{12}$</th>
<th>$F_{25}$</th>
<th>$F_{50}$</th>
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For SAO 183956, a fit to the observed near-IR excess could be obtained using 5-Å grains of silicate, close to thermal equilibrium, situated 0.2 au from the star. The temperature of such grains was ~1300 K, and a mass of $5 \times 10^{-7} M_\oplus$ was required to produce sufficient near-IR flux. For amorphous carbon grains, a distance of 0.4 au gave a good fit, with a temperature of 1300 K and a mass of $1 \times 10^{-6} M_\oplus$. These estimates are likely to be lower limits on the actual mass involved.

Using only small silicate grains gave too much contrast in the 10-μm silicate feature, implying that the near-IR excess is not due to only small silicate grains. Larger grains, with weaker 10-μm features, or grains of a different composition, must also be present. Adding the emission from small grains of AC to that of the silicate grains, in a 2:1 ratio, gives a silicate feature of similar strength to that observed. Combining the emission from this small-grain mixture with model M20p9a gives a good fit to the observed SED of SAO 183956 (Fig. 5). Details of the fit to the mid-IR spectrum of SAO 183956 are presented in Fig. 6.

No combination of models matched the 8–9 μm slope of the CGS3 spectrum. This wavelength region includes the wing of the
Figure 7. Results of modelling SAO 183986. Solid line: model B21p8; dotted line: effect of adding small thermal equilibrium silicate and AC grains (T = 1400 K) to model B21p8.

The combined model gives a good fit to the general shape of the 9-μm emission in the CGS3 spectrum. A superposition of these two small-grain models, with weighting factors of 0.8 for AC and 0.2 for silicate, gives a lower contrast silicate feature, which is in reasonable agreement with the observations could be obtained using 5-A AC grains at 0.08 au from the star. These grains were close to thermal equilibrium, with a peak in the probability distribution function at approximately 1400 K. A mass of 4×10⁻⁸ M_Earth of these grains was required to provide sufficient near-IR flux.

A similar fit could be obtained using 5 Å radius silicate grains at 0.04 au from the star. These had a peak temperature of approximately 1500 K, and a mass of 1×10⁻⁻⁸ M_Earth was required. However, these small silicate grains gave a strong silicate feature, exceeding the flux in the observed CGS3 spectrum. A superposition of these two small-grain models, with weighting factors of 0.8 for AC and 0.2 for silicate, gives a lower contrast silicate feature, which is in reasonable agreement with the 10–13 μm portion of the CGS3 spectrum. The effects of adding this model to model B21p8 are illustrated in Figs 7 and 8.

A grid of models was run using astronomical silicate grains (models M22–M2p71: see Table 5). The presence of UIR-band emission in the 10-μm spectrum of SAO 183986 meant that a good fit could not be obtained to the shape of the spectrum. The spectrum was therefore treated as an upper limit to the model flux in that wavelength region. The inner radius and mass of the disc were adjusted to fit the IRAS data at 25 and 60 μm.

A second grid of models (B22–B31) was calculated, using a mixture of 75 per cent silicate and 25 per cent AC grains. One of the best-fitting blend models, B21p8, is presented in Fig. 7.
6.5 SAO 184124 (HD 144432)

This A9/F0V star (Houk 1982) was first listed as a Vega-excess star by Walker & Wolstencroft (1988). Gregorio-Hetem et al. (1992) suggested that it is a Herbig Ae star, and Dunkin et al. (1997b) have illustrated its optical emission-line spectrum. It has the highest contrast silicate feature of any source in our sample (Paper I); this feature has also been detected by Walker & Butner (1995).

A grid of pure silicate models was run (models M31–M11p8: see Table 6), as well as a second grid using a mixture of silicate and AC grains, in a 3:1 ratio (models B31–B11p8). Model B21p3 gave good agreement with both JCMT points, and is presented in Fig. 9.

Using the small-grain technique to attempt to fit the near-IR excess of SAO 184124, it was found that both 5 and 3 Å radius grains of silicate or AC located 3.3 au from the star exhibited thermal spiking, but the resulting emission peaked at wavelengths that were too long to give a satisfactory fit to the observed near-IR excess. A good fit to the observed near-IR excess could be found for 5-Å silicate grains at 0.22 au, and for amorphous carbon grains of

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the same size at 0.47 au. The peak (near-equilibrium) temperatures of both grain species were approximately 1100 K. A mass of $6 \times 10^{-7} M_\text{Earth}$ of silicate grains, or $1 \times 10^{-6} M_\text{Earth}$ of AC grains, was needed.

Using only small silicate grains gave a 10-μm silicate feature with higher contrast than that observed in the CGS3 spectrum. Combining the two ‘hot’ small-grain models, with equal weightings, gave a reasonable fit to the CGS3 data. The effects of adding this combined model to disc model B21p3 are shown in Figs 9 and 10.

6.6 SAO 186777 (HD 169142)

SAO 186777 was first noted as a Vega-excess star by Walker & Wolstencroft (1988). It was classified as a B9V star by Houk (1982), and shows Hα in emission (Merrill & Burwell 1949). It has recently been reclassified as an A5 Ve star on the basis of echelle spectra (Dunkin et al. 1997a).

SAO 186777 was the first Vega-excess star discovered to show the UIR bands in its mid-IR spectrum (Sylvester, Barlow & Skinner 1994). Since the 20-μm spectrum of this source shows weak silicate emission, models were run using a mixture of silicate and amorphous carbon grains, with the carbon grains making up 20 per cent of the total dust mass. The new spectral type of A5 Ve from Dunkin et al. (1997a) was adopted.

Two models were run with a grain size parameter of $\gamma = 3$ (models B33, B31: see Table 7). Both gave significantly too little flux at millimetre wavelengths. Of the $\gamma = 2$ models, model B23 gave reasonable agreement with the JCMT data (Fig. 11), while model B22 gave mm-wave fluxes that were somewhat too high.

Essentially all of the model flux in the mid-IR is predicted to emerge from the inner few arcsec of the disc, so the difference between the CGS3 and IRAS fluxes does not appear to be due to a beam size effect. Scaling the CGS3 fluxes up by a factor of 1.3 gives good agreement between the IRAS and CGS3 fluxes at 12 μm, and between the model and the 20-μm spectrum (see Fig. 12).

Again, it was found that emission from 5 and 3 Å radius thermally spiking grains of silicate or AC peaked at longer wavelengths than the observed near-IR excess. Reducing the distance of the small grains from the star to 0.67 au for 5 Å radius grains of amorphous carbon gave good agreement with the observed near-IR excess. The grains were found to be close to thermal equilibrium, with a most probable temperature of 1150 K. A mass of $1.2 \times 10^{-6} M_\text{Earth}$ of such grains was required. Adding this model to model B23 gave good agreement to all the photometry, but slightly too much flux at 12 μm in the 10-μm spectrum (Fig. 12). Most of the 10 μm region flux can be seen to be due to emission in the 7.7-, 8.6- and 11.3-μm bands.

6.7 SAO 206462 (HD 135344)

Coulson & Walther (1995) made extensive optical, IR and mm-wave observations of this star. They found that its spectral type is misclassified in the SAO catalogue: it shares the same HD number
as SAO 206463, and the A2 classification appropriate for SAO 206463 is repeated for SAO 206462. The Michigan catalogue gives a combined spectral type of AOV. Coulson & Walther determined a spectral type for SAO 206462 of F8V. An F-type classification is consistent with the observations of Oudmaijer et al. (1992: F4Ve), Zuckerman et al. (1995: F6V) and Dunkin et al. (1997a: F4Ve).

Coulson & Walther (1995) modelled the IR excess emission of SAO 206462 with two blackbodies - one of temperature 1500 K, which fitted the near-IR excess, and one of temperature 95 K, which fitted the long-wavelength data.

A grid of grain blend models was run (models B22–B2p73: Table 8), along with two models using only AC grains (models C21–C11). No attempt was made to fit the IRAS fluxes at 25 and 60 μm. Given that the long-wavelength tail of the strong near-IR excess may contribute to the 12-μm flux, the IRAS 12-μm point was treated as an upper limit to the flux from the equilibrium models. Model M21p3 gives a good fit to the data from 25 μm to 1 mm, and is presented in Fig. 13.

A further grid (models B22–B11p7) was produced, using a blend of 75 per cent silicate and 25 per cent AC grains. Similar results were obtained as for the pure silicate models.

Two models were run using only AC grains (models C11 and C0p50p5). Both gave significantly too little long-wavelength flux, even with rather low values of ρ and β.

The near-IR excess of SAO 226057 was modelled using the small-grain technique. Grains of radius 5 Å located 67 au from the star (the inner radius of model M21p3) showed departures from thermal equilibrium, but the peak wavelength of the resulting emission spectrum was too long.

3 Å radius grains gave better results, although the fit to the near-IR observations was not perfect, with too much flux in the M band, and too little at H. A harder UV–optical radiation field than that predicted by the Kurucz model atmosphere would increase the probability of high-temperature excursions, and so cause the small-grain emission to peak at shorter wavelengths.

The narrow-band 10-μm photometry of van der Veen et al. (1989) of SAO 226057 does not suggest the presence of a strong silicate feature, so only amorphous carbon grains were considered in the small-grain modelling. The mass of thermally spiking small grains at 67 au required to reproduce the near-IR flux distribution...
Table 8. Models for SAO 206462 (HD 135344).

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<td>25.7</td>
<td>21.6</td>
<td>373</td>
<td>135</td>
</tr>
<tr>
<td>C11</td>
<td>1</td>
<td>1</td>
<td>23</td>
<td>840</td>
<td>$2.4 \times 10^{-3}$</td>
<td>1000</td>
<td>0.15</td>
<td>6.4</td>
<td>25.6</td>
<td>20.7</td>
<td>344</td>
<td>124</td>
</tr>
</tbody>
</table>

The effects of adding thermally spiking grains to model M21p3 are shown in Fig. 15.

7 DISCUSSION

Table 10 lists the parameters of the best-fitting models of the set of eight stars modelled in this paper, as well as those from Paper II. The stars are ordered by spectral type. The power-law indices $\gamma$ and $\beta$ do not appear to correlate with spectral type. The derived values of the grain-size power-law index $\gamma$ lie in the range 2–3. An MRN-like distribution (Mathis, Rumpl & Nordsieck 1977) would have $\gamma=2.5$ (Paper II), so it appears that the grain size distribution in Vega-like discs may resemble the MRN distribution, extended to larger grain sizes. All the models used minimum and maximum grain radii of 50 Å and 1000 μm respectively. For $\gamma < 3$, the majority of the grain mass resides in the largest grains in the distribution. When the maximum grain size is unknown, therefore, the total dust mass is poorly constrained. There is some tendency for the later type stars to have lower disc masses. Also, of the six G- or K-type stars, only one has a near-IR excess, while of the six stars of type A5 or earlier,
fractional excess luminosities, and the SED of the excess emission is well defined by the observations over a large wavelength range. However, separating the models for the near-IR excess from the equilibrium models leads to some uncertainty in the interpretation of the CGS3 spectra, as the small grains can be responsible for a noticeable fraction of the 10-\mu m silicate emission. The CGS3 spectra are thus less useful for constraining the grain size distribution parameter \( \gamma \) than might be hoped. On the other hand, the stars in the current paper have good mm-wave detections, allowing us to put constraints on \( \gamma \) using the mm-wave emission from large grains (see Paper II for discussion of the effects of the modelling parameters). Imaging observations in the IR or submm would help to constrain the models, by providing an independent determination of the disc density distribution parameter \( \beta \).

The thermal equilibrium disc models alone do not always provide sufficient contrast in the 10-\mu m silicate feature; this is because the grain size distributions must contain an amount of large grains (which show no silicate feature) that is sufficient to provide the observed mm-wave emission. A size distribution that was not described by a single power law could, in principle, give the right proportions of small and large grains to fit both the long-wavelength emission and the silicate features, without requiring any contribution to the feature contrast from the very small grains. However, such a distribution would mean introducing more free parameters into the distribution.

Thermally spiking small grains do not generally give good fits to the observed near-IR excess SEDs. Reasonable fits were obtained using the mm-wave emission from thermally spiking 3\AA radii grains for SAO 77144 and 131926, which are both classified as early A-type stars, and are the hottest of our stars to show near-IR excesses. For the other stars, the resulting SEDs from spiking grains peaked at wavelengths that were too long. Hotter stars will emit more UV photons, so it is likely that they will more easily excite small grains to high temperatures. Emission from thermally spiking grains could be responsible for the near-IR excesses of the other stars if there is, for instance, excess UV emission from the stars, or the small grains have a greater UV absorption cross-section than was adopted for the stars in the current paper. Reasonable fits to the observed near-IR excess SEDs were too long. Hotter stars will emit more UV photons, so it is likely that they will more easily excite small grains to high temperatures. Emission from thermally spiking grains could be responsible for the near-IR excesses of the other stars if there is, for instance, excess UV emission from the stars, or the small grains have a greater UV absorption cross-section than was adopted for the present modelling. However, given the large range of luminosities for the observed near-IR excess SEDs, it seems highly unlikely that any of the stars could have sufficiently large UV excesses to power the observed near-IR luminosities.

Leger & d'Hendecourt (1987) have shown that small graphitic clusters only absorb photons with energy greater than...
The large fractional excess luminosities of these stars (Table I) imply the discs cannot be physically thin and emitting only reprocessed starlight. To intercept enough starlight, reprocessing ‘discs’ must subtend a large solid angle, i.e. they must be substantially flared, or alternatively some of the dust may reside in a spherical envelope. Many HAeBe stars are believed to possess large spherical envelopes as well as discs. It is of interest to consider whether the double-peaked Vega-excess SEDs could be due to a hot disc and a cooler, more distant envelope. Because our models are optically thin, the SED of a spherical envelope is identical to that of a disc with the same parameters (γ, β, etc.). We can therefore immediately compare the derived properties of the discs with those of HAeBe envelopes. Natta et al. (1993b) derived envelope inner radii in the range ~1400–2 x 10^4 au for a sample of five HAeBe stars; the envelope masses were all greater than ~10 M_⊙. In contrast, the disc masses in Table 10 are all less than 10^−3 M_⊙. The inner radii we derive for Vega-like systems are much smaller than those found by Natta et al. for the HAeBe envelopes; only SAO 131926 has an inner radius within a factor of 10 of the smallest HAeBe envelope inner radius. Hence if the dust around these ‘extreme’ Vega-excess stars is distributed in spherical envelopes, they are very different from HAeBe envelopes.

Another possible explanation for the large fractional excess luminosities is intrinsic disc luminosity. This can arise from the conversion of gravitational potential energy due to material accreting through the disc. If we assume that the discs intercept and re-radiate the ‘flat disc’ maximum of 0.25L*, then the remaining excess luminosity L_4 is intrinsic to the disc, and can be assumed to be due to accretion. We can then derive the accretion luminosity and the mass accretion rate M_ace using the relation M_ace = R_4 L_4/GM_*, (see Natta et al. 1993b for details). The values of M_ace calculated for our stars are presented in Table 11. These values seem plausible: the largest value (for SAO 131926) is comparable to the smallest values derived by Hillenbrand et al. (1992) for a sample of 23 HAeBe stars, while the others are all smaller than any derived by Hillenbrand et al. They are also considerably smaller than the typical protostellar accretion rate of 10^{-5} M_⊙ yr^{-1} adopted by Palla & Stahler (1993).
three have near-IR excesses. However, our sample size is too small to claim a strong correlation.

As shown in the preceding figures and tables, the combined models can give very good fits to the observational data. The equilibrium models are rather well constrained. This agrees with the results of Paper II: the current sample (0.14-0.64) is too small and large grains to fit both the long-wavelength determination of the disc density distribution parameter $\beta$. Modeling parameters).

Thermally spiking small grains do not generally give good fits to the observed near-IR excess SEDs. Reasonable fits were obtained with thermally spiking 3Å radius grains for SAO 77144 and 131926, which are both classified as early A-type stars, and are the hottest of our stars to show near-IR excesses. For the other stars, the resulting SEDs from spiking grains peaked at wavelengths that were too long. Hotter stars will emit more UV photons, so it is to be expected that they will more easily excite small grains to high temperatures. Emission from thermally spiking grains could be responsible for the near-IR excesses of the other stars if there is, for instance, excess UV emission from the stars, or the small grains have a greater UV absorption cross-section than was adopted for the present modelling. However, given the large uncertainties in the interpretation of the CGS3 spectra, as the small grains can be responsible for a noticeable fraction of the 10-μm silicate emission. The CGS3 spectra are thus less useful for constraining the grain size distribution parameter $\gamma$ than might be hoped. On the other hand, the stars in the current sample have good mm-wave detections, allowing us to put constraints on $\gamma$ using the mm-wave emission from large grains (see Paper II for discussion of the effects of the modelling parameters). Imaging observations in the IR or submm would help to constrain the models, by providing an independent determination of the disc density distribution parameter $\beta$.

The thermal equilibrium disc models alone do not always provide sufficient contrast in the 10-μm silicate feature; this is because the grain size distributions must contain an amount of large grains (which show no silicate feature) that is sufficient to provide the observed mm-wave emission. A size distribution that was not described by a single power law could, in principle, give the right proportions of small and large grains to fit both the long-wavelength emission and the silicate features, without requiring any contribution to the feature contrast from the very small grains. However, such a distribution would mean introducing more free parameters into the distribution.

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unreddened, the model $E(B - V)$ is 0.24, while $r_V$ is 0.62; the dust therefore cannot be distributed in a shell and have the properties adopted for the models that fit the SED. To obtain a shell that gives sufficient $L_{IR}/L_*$ without appreciable reddening would require dust with a high $R_V$ (ratio of total to selective extinction). This implies a much shallower grain size distribution than used by the best-fitted model. Such a distribution would have emission properties inconsistent with the observations, giving much larger far-IR and mm-wave fluxes than are observed (Table 8). A disc therefore remains the most plausible distribution for the matter around this star.

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NOTE ADDED IN PROOF

Hipparcos parallaxes have recently been published (ESA 1997) for three of the stars in this paper: SAO 77144, 131926 and 184124 have parallaxes of $6.7\pm2.5$, $6.1\pm1.6$ and $4.0\pm1.0$ milliarcsec respectively, giving distances of $150\pm50$, $160\pm40$ and $250\pm90$ pc. Comparing these with the adopted distances in Table 1, we find that SAO 77144 is slightly closer than the adopted distance, while SAO 184124 is at least twice as distant as our estimate, which suggests that there could be a considerable amount of dust extinction in the line of sight, which could be due to an edge-on disc, as postulated by Bogaert & Waelkens (1991).

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