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THE DUST DISK AROUND THE VEGA-EXCESS STAR SAO 26804

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ABSTRACT

We present multiwaveband observations of the K2 Vega-excess star SAO 26804 (=HD 233517). These include James Clerk Maxwell Telescope millimeter-wave photometry, plus spectra in the 8–13 μm and 18–24 μm atmospheric windows, an image at a wavelength of 10 μm through a broadband *N* filter and near-IR (*JHKLL′M*) photometry all taken at the United Kingdom Infrared Telescope. The source is resolved at 10 μm, and we can confirm with these observations that the IR excess seen in *IRAS* observations of this source is associated with the optical star. The image is consistent with the dust being confined to a disk with FWHM 1″.5 on the major axis, with an inclination angle of less than 30° away from edge-on. This represents the first confirmation that the dust in a Vega-excess star other than β Pic is confined to a disk geometry. We present models of the source which show that many of the properties of the disk and the dust in it are similar to those which we have previously derived for the disk around SAO 179815, but that there are some very small grains in the disk around the star which give rise to a very prominent and narrow silicate dust feature at 9.7 μm and to so-called unidentified infrared bands in the 10 μm region. The larger grains are composed of a mixture of amorphous carbon and silicate with an abundance ratio consistent with an interstellar origin. The total mass of dust in the disk is $3.0 \times 10^{-7}\ M_{\odot}$. Finally, our model suggests that there may be a substantial UV and/or soft X-ray flux from SAO 26804, consistent with it being a very young and rather active star.

Subject headings: accretion, accretion disks — circumstellar matter — dust: extinction — infrared: stars — stars: imaging — stars: individual (SAO 26804)

1. INTRODUCTION

The first evidence for protoplanetary disks in stellar systems other than our own was the far-IR excess in the spectrum of Vega, discovered during the *IRAS* mission (Aumann et al. 1984). Gillett (1986) subsequently described circumstellar excesses, determined from *IRAS* pointed observations, around three more main-sequence stars. The initial observations with *IRAS* of Vega were found to be indicative of a large dust disk, whose inner edge is at many tens of AU from the star, and which is seen approximately face-on in the case of Vega. The dust was suggested then and is still believed now to be a remnant from the stellar, and perhaps planetary, formation phase. Aumann (1985) identified, from *IRAS* survey observations, eight more nearby "Vega-excess" stars and at present several dozen probable examples are known. The most extensively studied of such disks has been that around β Pic, owing to its size, large IR excess, and proximity to the solar system.

Smith & Terrile (1984) presented photographic IR CCD images of β Pic, while Paresce & Burrows (1987) obtained *BVRI* coronagraphic images of the disk. Artymowicz, Burrows, & Paresce (1989) constructed detailed models to account for the optical properties of the disk by scattering off the dust grains, with the far-IR fluxes produced by thermal emission from the same grains. Unfortunately, the assumed properties of the grains do not resemble measured laboratory properties of dust grains. Their results may thus need to be treated with some caution.

On the basis of their models, Artymowicz et al. suggest that the grains could be of a single size, and either "large" ($r_g > 20$ μm) or "midsize" (1 μm $< r_g <$ 20 μm). Their results indicated that the grain radii are most likely principally in the range 1 μm $< r_g <$ 20 μm and that the dust grain number density ρ_g varies as the inverse cube of distance d from the central star (i.e., $\rho_g \propto d^{-3}$). On the basis of submillimeter observations, Becklin & Zuckerman (1990) suggested that the radii of the principal radiating grains lie in the range 3 μm $< r_g <$ 100 μm for Vega and α PsA, and $r_g <$ 3 μm for β Pic. From narrowband photometry, Telesco & Knacke (1991) inferred the presence of silicate grains in the β Pic disk. The first fully resolved mid-IR spectra of β Pic were obtained by Aitken et al. (1993) and Knacke et al. (1993), who concluded from the shape of the 9.7 μm silicate feature that the dominant grain size was of order 2 μm. There are thus moderately good constraints on typical grain sizes in the β Pic disk, if not on the size distribution, but in other Vega-excess disks the situation is less clear.

Using a bolometer array, Telesco et al. (1988) tentatively resolved the β Pic disk at 10.8 and 19.2 μm, confirming that the dust radiating at these wavelengths is indeed physically associated with that scattering optical radiation in the disk and concluding that the grains at 80 AU from the star were typically less than 1 μm in radius. The dust around β Pic was confirmed to be in a disk by the striking images presented by Lagage & Pantin (1994). The latter authors suggested that at the time of writing they had not detected extension around any other Vega-excess star in the mid-IR.

At this point, we are presented with the possible presence in these systems of an unspecified distribution of large grains,

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midsize grains, and small grains, which probably contain silicates as a constituent.

We presented the first consistent model of the thermal emission by grains in a Vega-excess disk (Skinner, Barlow, & Justtanont 1992, hereafter as SBJ), in which we showed how multiwavelength observations can be used to provide useful constraints on the distribution of grain sizes in a passively reradiating disk. SBJ studied the K5 V star SAO 179815, which before our work had only received attention on account of the possibility that it is a nearby binary star system. It is basically unreddened optically and in the near-IR, but has a very large excess in the mid- and far-IR. It displays a very broad silicate emission feature peaking at 9.7 μm and has a very low spectral index in the far-IR and submillimeter, the latter property being shared by many other Vega-excess stars (Sylvester, Barlow, & Skinner 1994b). SBJ showed that its disk contained grains with a power-law distribution of grain sizes which was biased somewhat more toward large grains than the usual interstellar grain size distribution derived by Mathis, Rumpl, & Nordsieck (1977). The smallest grains in the disk around SAO 179815 we showed must be at least as small as 0.05 μm, and the largest probably exceed 100 μm in radius. Considerable follow-up work on this star has included some mid-IR photometry by Zuckerman & Becklin (1993), which confirmed our spectroscopic identification of silicate dust in the disk, and optical spectroscopy by Fekel & Bopp (1993), which showed that SAO 179815 is probably a BY Draconis star, very young and with an active chromosphere. As emphasized by Sylvester, Barlow, & Skinner (1992), and by Zuckerman & Becklin (1993), the IR excess of SAO 179815 is remarkably large: the fraction of the star's total luminosity emitted by dust, L_{IR}/L_*, is $\sim$0.1, compared with only of order 10^{-3} for β Pic, which has often been considered to have a large excess for a Vega-excess star, and 2.3×10^{-5} for Vega itself. Zuckerman & Becklin described SAO 179815 as in many ways "the most unusual source in the *IRAS* catalogs" because of its large IR excess. In fact Walker & Wolstencroft (1988) published a very useful list of Vega-excess stars, many of which have IR excesses comparable with or exceeding that of SAO 179815 (Sylvester et al. 1992). This, together with the work of Fekel & Bopp (1993), must raise the possibility that a significant number of these Vega-excess stars may be very young, either just arrived on the main sequence or perhaps even pre–main-sequence still.

Therefore we are carrying out a survey of the properties of Vega-excess stars, including initially photometry and spectroscopy in the near-IR, mid-IR, and submillimeter wavelength regions. Some early results of this survey have been published by Sylvester et al. (1992, 1994b). In this paper we present results of a comprehensive study of the K2 Vega-excess star SAO 26804. This is another cool star which appears to be unreddened optically, but which like SAO 179815 has a large IR excess: $L_{IR}/L_* = 0.036$. In the latter respect it resembles many of the other sources in our survey, upon which we will be reporting in forthcoming papers. In the following section we present the observations of the star; in § 3 we discuss our models of it; and finally in § 4 we discuss our model results and their implications.

2. OBSERVATIONS

We have obtained near-IR photometry, mid-IR spectra and a mid-IR image, and millimeter-wave photometry of SAO 26804. The observations are summarized in Table 1 and presented in Figure 2, and we describe details of the observations in this section.

TABLE 1

OBSERVED FLUXES OF SAO 26804

Wavelength or Waveband	F_λ (W m^{-2} μm^{-1})	Beam	Source
B	3.32×10^{-12}	...	WW[a]
V	6.41×10^{-12}	...	WW[a]
J	3.70×10^{-12}	7".8	UKT9
H	2.19×10^{-12}	7.8	UKT9
K	8.97×10^{-13}	7.8	UKT9
L	1.43×10^{-13}	7.8	UKT9
L'	1.17×10^{-13}	7.8	UKT9
M	4.74×10^{-14}	7.8	UKT9
10.0 μm	8.85×10^{-15}	5.5	CGS3
N	1.29×10^{-14}	Image	Berkcam
12 μm	7.60×10^{-15}	$\sim$45	*IRAS*
20.0 μm	1.45×10^{-14}	5.5	CGS3
25 μm	1.90×10^{-14}	$\sim$55	*IRAS*
60 μm	6.15×10^{-15}	$\sim$90	*IRAS*
100 μm	1.44×10^{-15}	$\sim$180	*IRAS*
1100 μm	$<8.93 \times 10^{-20}$	18.5	UKT14

[a] WW: photometry quoted by Walker & Wolstencroft 1988.

We have attempted submillimeter photometry of SAO 26804 at the 15 m James Clerk Maxwell Telescope (JCMT) on a number of occasions, but on each instance have suffered either technical problems or indifferent weather conditions. Our best upper limit was obtained in 1992 March, when a 3 σ upper limit of 36 mJy at a wavelength of 1100 μm was derived, using the common-user bolometer UKT14 (Duncan et al. 1990). This upper limit places an important constraint on the maximum grain size in the disk, which we will discuss later.

Near-IR photometry was obtained for us at the 3.8 m United Kingdom Infrared Telescope (UKIRT) in service mode using the common-user photometer UKT9, at the *J*, *H*, *K*, *L*, *L'*, and *M* wavebands. These observations were made on 1993 February 10 and calibrated against the standard stars HR 2228, HR 3888, and GL 390. Details of the near-IR and JCMT photometry are summarized in Table 1.

Mid-IR spectra were taken at UKIRT on 1993 May 31 (18–24 μm) and 1993 June 1 (8–13 μm) with the common-user mid-IR spectrometer CGS3. The spectral resolving powers employed were $\sim$65 in the 10 μm atmospheric window and $\sim$70 in the 20 μm window. Spectra were taken through a 5".5 circular aperture, and 30" east-west chopping was used to effect sky cancellation. The spectra were flux-calibrated against the standard stars α Boo and μ UMa. The on-source integration times were $\sim$23 minutes for the 10 μm spectrum and $\sim$12 minutes for the 20 μm spectrum. The spectra were taken in 20 s cycles, the telescope being nodded between cycles, and the errors plotted in Figure 1 are the 1 σ deviations in the co-added integrations. Typical errors in the 10 μm spectrum of SAO 26804 are about $\pm 2 \times 10^{-15}$ W m^{-2} μm^{-1}, corresponding to $\sim 10^{-14}$ W m^{-2} μm^{-1} in 1 minute, which is fairly typical for CGS3. The errors are somewhat larger than this only in the 9.4–10.0 μm range where the telluric ozone emission is strong. The calculated errors in the 20 μm spectrum are likewise fairly typical for CGS3 on a dry night, with the errors somewhat larger at the wavelengths of known water vapor absorption bands. SAO 26804 has a 12 μm *IRAS* point source flux of only 0.4 Jy, and so despite fairly lengthy integration times our spectra are still somewhat noisy. If we convolve our CGS3 spectra with the *IRAS* 12 and 25 μm bandpasses we find that our spectra agree nicely with the *IRAS* fluxes to within their uncertainties.

Finally, we obtained an image in the mid-IR using the Berkeley/Livermore mid-IR camera (Berkcam) at UKIRT on 1992 December 5. Observations were taken through a broadband *N* filter, and calibrators used were β Gem, HR 2990, and HR 3275. All other details of the observations were as described by Keto et al. (1991). The pixel size was 0″.4, and each observation consisted of a 10 × 16 pixel panel, and we mosaicked around the source to minimize effects of imperfect flat-field response correction and to ensure that we completely covered any extended emission. As a result we had 370 individual frames of SAO 26804. These were individually registered to take account of telescope drift as well as our deliberate telescope movements. β Gem was used as the photometric standard, and the other two calibrators were merely used to check that atmospheric transmission had not changed dramatically during the course of our long integrations on SAO 26804, and that the point-spread function did not change significantly. To the accuracy of our final image of SAO 26804 the point-spread function did not change at all. The FWHM of β Gem in our images is ∼1″.1 in both declination and right ascension, while the FWHM of SAO 26804 is ∼1″.1 in right ascension and ∼1″.5 in declination. The uncertainties of these measurements, based on the stability of the point-spread functions of the three calibrators observed at different times, and the rms uncertainties in the SAO 26804 image, are about ±0″.05 for the calibrators and ±0″.1 for SAO 26804. The image of SAO 26804 is elongated with semimajor axis at a position angle of ∼20° east of north. Our measured *N*-band flux density is 0.43 Jy, identical to the *IRAS* 12 μm flux, which given the shape of the spectrum in this region is entirely reasonable.

The mid-IR spectra are presented in Figure 1, and the complete spectral energy distribution (SED) including all the photometry and the spectra described above in Figure 2. The mid-IR images of SAO 26804 and of β Gem are shown in Figure 3 (Plate 32). Table 1 summarizes the flux density measurements of the star at various wavelengths.

3. ANALYSIS

The SED of this source is generally very similar to that of SAO 179815, which was modeled in some detail by SBJ. The far-IR photometry by *IRAS* shows a very slow decrease in flux with wavelength as in SAO 179815, indicating the presence of very large grains. Our near-IR photometry confirms that there is no excess in the 1–5 μm region due to a large population of small grains. However, the 10 μm spectrum of SAO 26804 is

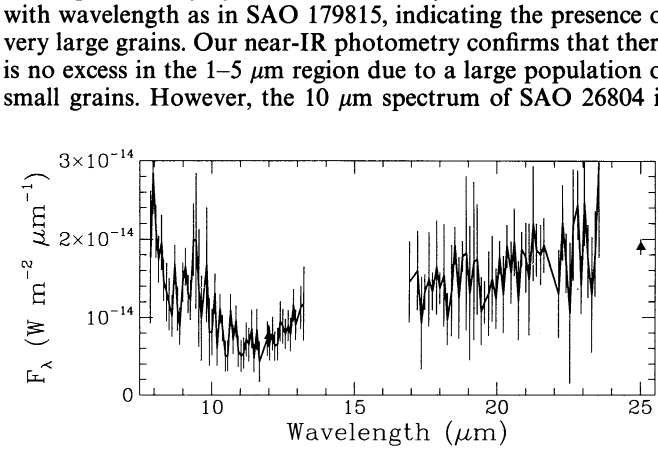

FIG. 1.—CGS3 spectra of SAO 26804. The S/N is rather poor (typically ∼5 σ per point), but the important observed structure, which is real, is the very rapidly falling flux from 8 to 9 μm, the rather narrow silicate feature in the 9–11 μm region, and the rapidly rising continuum longward of 11 μm.

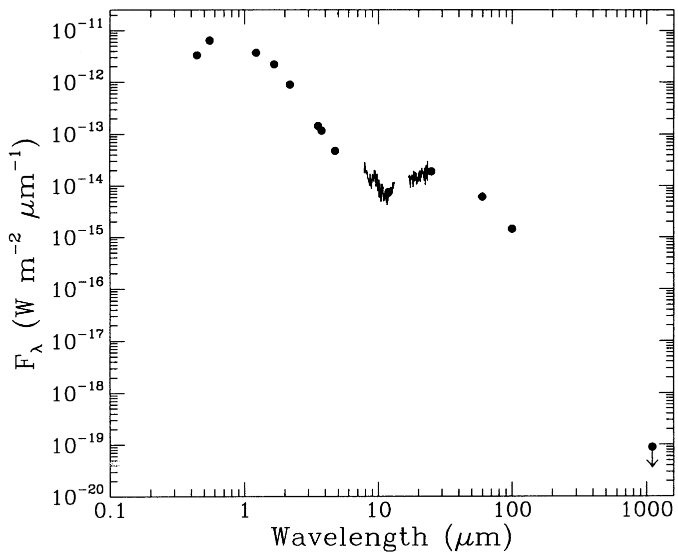

FIG. 2.—Complete SED of SAO 26804. The sources of all the data are listed in Table 1.

rather peculiar. In SAO 179815 all we saw in this region was a fairly flat continuum and a very broad, rather weak silicate feature. SAO 26804 in contrast appears to show a fairly strong and quite narrow silicate feature, which would not initially appear to be in keeping with the large grain sizes implied by the longer wavelength photometry. Additionally, we see a continuum rising very rapidly with decreasing wavelength shortward of 9 μm, and likewise a rapid rise in flux with increasing wavelength longward of ∼11.5 μm.

Before proceeding, we briefly discuss the effects of the telluric ozone band on our 8–13 μm spectrum. Given the unusual nature of the SAO 26804 spectrum (which will become more apparent through the following sections), one must consider the possibility that poor cancellation of the ozone band could contribute to the "silicate" feature. If we examine the underlying continuum (see, e.g., the dotted line in Fig. 11*b*), we are forced to conclude that there is excess emission, above any smooth continuum, in the wavelength range 8.0–11.0 μm. We will see later that in the 8.0–9.0 μm range we can explain much of this excess as coming from polycyclic aromatic hydrocarbons (PAHs), but between 9.0 and 11.0 μm there are no known PAH features, and we must attribute the large excess in this wavelength region to some other source. Strong telluric ozone emission is seen between about 9.4 and 10.0 μm, and we have never experienced any problems with atmospheric cancellation outside this range. Ozone cancellation was good in spectra taken throughout the night we observed SAO 26804, and adjacent nights. If we calibrate our SAO 26804 data against standard stars observed at different times and air masses, we find that the flux in the 9.4–10.0 μm region is somewhat reduced or increased, but that a much broader emission feature still appears to be present in all cases. In various CGS3 spectra where the ozone is poorly canceled, the residual ozone feature spans typically six to eight data points, and always less than 10. The emission feature in our SAO 26804 spectrum spans at least 25 data points and is therefore at least a factor of 3 broader than the worst residual ozone effects we have encountered. We therefore feel confident in ascribing the broad 9–11 μm emission feature in SAO 26804 to dust.

In this section we will present models of the disk around

SAO 26804, with which we attempt to explain the observed properties. We have used the code described by SBJ to model the SED of SAO 26804. However, we have made a number of improvements to the code. First, we now use model-atmosphere spectra to represent the stellar radiation field, rather than the blackbody approximation used previously. The model atmospheres are due to Kurucz (1991). Second, we have included the effects of scattering in the code. We assume isotropic scattering, thus ignoring the probably nonnegligible effects of forward peaked scattering. Since the code is optically thin, the calculated scattering effect will only be a good approximation so long as the scattering optical depth remains reasonably small. Third the code can now output spatial information about the scattered and thermal radiation from the disk at various wavelengths, for comparison with images.

3.1. *The Central Star*

In order to construct models of the disk around SAO 26804 we first need to determine the parameters for the central star. It is classified in the SAO catalog as a K2 star (note the error by Walker & Wolstencroft 1988, who listed its spectral type as A2). Currently there is no luminosity classification of this star, and we adopt the Kurucz model atmosphere for a star with effective temperature 4500 K and surface gravity log $g = 4.5$. With $L_*/L_\odot \sim 0.28$ for a K2 V star, we find that the star should be at a distance of $\sim$25 pc.

It is of course possible that SAO 26804 is not in fact a dwarf star, and we discuss the arguments against this here. First, our near-IR photometry is exactly in agreement with the Kurucz model for a solar metallicity K2 dwarf. In the case that the star is of some other luminosity class, the photometry not in such good agreement with model predictions. SAO 26804 has a high Galactic latitude, in excess of 40°. If it were of luminosity class III, then with a standard $M_V = +0.2$ its distance must be of order 1 kpc, its height above the Galactic plane also approaching 1 kpc. At this height, it could not be a massive star. There are no known K III stars with circumstellar dust shells, except for some post-AGB stars, and these all have significantly reddened spectra, while SAO 26804 has essentially zero reddening. Given its large IR excess, the negligible reddening implies that the substantial amount of dust must be in a disk, which must be fairly thin. We will conclude later that the disk around SAO 26804 must have both oxygen-rich and carbon-rich grains and that the grain sizes vary between a few angstroms and 100 μm: these conclusions will hold regardless of the luminosity of the star. Such large grains have never been observed in any post–main-sequence star, except perhaps for the remarkable R star HD 100764 (Skinner 1994), and if SAO 26804 were in fact a post–main-sequence star then its possession of both oxygen-rich and carbon-rich grains would probably be unique. Therefore SAO 26804 could either be a dwarf with a dusty disk, similar to various other Vega-excess stars, or possibly the most extraordinary post–main-sequence star so far discovered. Henceforth, we will assume that it is a dwarf (we include in the term "dwarf" such slightly pre–main-sequence stars as SAO 179815).

The K5 V component of SAO 179815 was discovered by Fekel & Bopp (1993) to be a BY Draconis star, which implies it will probably have an active chromosphere with strong UV line emission. Dust grains in a disk around such a star will absorb UV photons very efficiently, and so the thermal emission by the disk may be affected by the presence of an active chromosphere. We have therefore constructed possible model spectra to use as input radiation fields, by adding to the Kurucz model-atmosphere spectra lines of strengths measured in a number of stars in *IUE* spectra. For a normal K2 V star we ignore the effects of UV line emission altogether. The K2 V star ϵ Eri serves as a prototype for a fairly active K dwarf star, and we take absolute values for the surface fluxes in the N v λ1240, O I λ1304, C II λ1335, Si IV + O IV λ1400, C IV λ1549, He II λ1640, C I λ1657, Si II λ1810, Fe II λ2610, and Mg II λ2800 lines from Linsky et al. (1982). Fekel et al. (1988) obtained *IUE* short-wavelength spectra of the K2 Ve BY Draconis star, HD 82558, and the surface line strengths appear to be almost identical to those reported by Rucinski (1985) for the K0 Ve star HD 36705, which is the most rapidly rotating K dwarf known and very chromospherically active. We thus use the absolute surface fluxes for the lines in HD 36705 as an example of the most extreme form of chromospheric activity likely. In Figure 4 we present the short-wavelength model-atmosphere spectrum of Kurucz (1991) and show the line strengths for HD 36705 folded into the spectrum at the appropriate resolution. Line strengths for ϵ Eri are about an order of magnitude fainter, and those for a normal K dwarf, as reported by Linsky et al. (1982) and Ayres, Marstad, & Linsky (1981), about another order of magnitude fainter still. When we include the UV line fluxes in various models for disks with grains of interstellar or larger size ($r_g > 0.005$ μm) we find that the grain temperatures are typically increased by only 1% or so over those for a K dwarf with no UV line emission whatever, even for lines as bright as those in HD 36705. Since SAO 179815 was found to be a BY Draconis star, and Fekel et al. (1988) demonstrate that BY Draconis stars may have extreme levels of chromospheric activity (by the standards of K dwarfs at least), and the IR excess in SAO 26804 is approaching that of SAO 179815 in magnitude, we include HD 36705 line fluxes in all the models we describe in this paper. We will see later that these lines may have a significant effect on our final models, which include very small grains.

3.2. *Interstellar and Larger Sized Grains*

As for SAO 179815, we consider the circumstellar disk to extend from an inner radius $d_{\rm in}$ to an outer radius where the

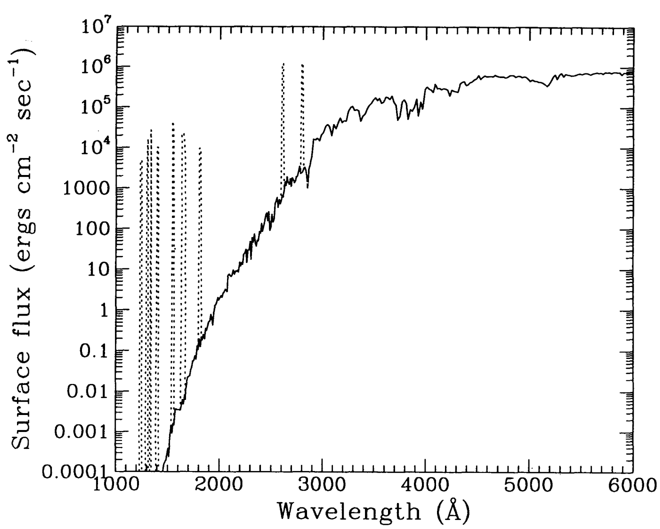

FIG. 4.—Adopted stellar radiation field. The solid line indicates the standard Kurucz (1991) stellar atmosphere model, and with dotted lines we show the UV line fluxes adopted for a BY Draconis type star.

dust temperature approaches equilibrium with the interstellar radiation field. The mass density of the disk, ρ_d, is assumed to vary with radius, d, as $\rho_d \propto d^{-\beta}$. Grains in the disk are assumed to lie in the size range $r_{\min} < r_g < r_{\max}$ and to have a size distribution $n(r_g) \propto r_g^{-\alpha}$. For SAO 179815 the best-fitting model of SBJ had $\alpha = 3.0$, $\beta = 2.0$, $r_{\min} \sim 0.01$ μm, and $r_{\max} > 100$ μm.

Two grain removal processes are of concern to us in assembling models of Vega-excess disks—the Poynting-Robertson drag (PRD) and radiation pressure expulsion or "blowout." PRD results in the decay of orbits of small grains around stars and selectively removes the smallest grains from a disk. An expression for the PRD can be used to estimate an orbital decay timescale of

$$\tau_{\rm PR} = 710 r_g \rho_g d^2 \frac{L_\odot}{L_*} \text{ yr} \quad (1)$$

(Burns, Lamy, & Soter 1979), where r_g is the grain radius in microns, ρ_g is the mass density of the grain material in cgs units, d is the orbital radius, and $\tau_{\rm PR}$ is the orbital decay timescale in years. Thus for a silicate grain of radius 0.01 μm orbiting 10 AU from a K2 V star, the orbital decay timescale is $\sim$8400 yr. We may therefore expect PRD to be important in influencing the number of small grains orbiting in a disk around such a star. However, the fact that we see 9.7 μm silicate emission features in Vega-excess stars (see this work; SBJ; Aitken et al. 1993) shows that, even if some of the small grains do spiral into the star due to the PRD, they must be replenished in the disk, presumably by grain collisions. Hence, for now we will ignore PRD in consideration of our grain size distribution.

Radiative blowout has been shown to selectively remove grains in a certain size regime from a stellar environment. For instance, in our solar system the maximum in the ratio γ of outward radiation pressure to inward gravitational attraction has been shown to occur at a grain radius of $\sim$0.25 μm (Burns et al. 1979). However, γ never becomes greater than 1.0 for any grain radius or grain material in the solar system; hence blowout is unimportant for the Sun. In the case of β Pic on the other hand, Artymowicz (1988) showed that silicate grains in a range of submicron sizes would be expelled from the system by this radiative blowout effect. We have used the equation for the ratio of radiative to gravitational pressure (e.g., Backman & Paresce 1993),

$$\gamma(r) = \frac{3L_* \langle Q_{\rm pr}(r_g) \rangle}{16\pi G M_* c r_g \rho_g}, \quad (2)$$

where $\langle Q_{\rm pr}(r_g) \rangle$ is defined as

$$\langle Q_{\rm pr}(r_g) \rangle = \frac{\int F_\lambda Q_{\rm pr}(r_g, \lambda) d\lambda}{\int F_\lambda d\lambda} \quad (3)$$

and G is the gravitational constant, L_* and M_* are the stellar luminosity and mass, c is the speed of light, r_g is the grain radius, and ρ_g is the mass density of the grain material. The resulting values of $\gamma(r)$ are plotted in Figure 5 and show that, as expected, SAO 26804 is insufficiently hot or luminous to expel grains of any size or material from its environment. We note that, for amorphous carbon grains, the value of $\gamma(r)$ does just barely exceed unity in the size range 0.1–0.3 μm, and it is possible that grains close to this size range might be selectively removed. However, this range of sizes is tiny compared with the full range of sizes being considered for our disk models, and the removal of all grains in this small range of sizes would have a very small effect on our models, and so we henceforth ignore radiative blowout for this star. Therefore, we would predict that in the disk around SAO 26804, as in that around SAO 179815, $r_{\min}$ should be close to the value in the interstellar medium, of order 0.005 μm or so, and we use this value in the following models.

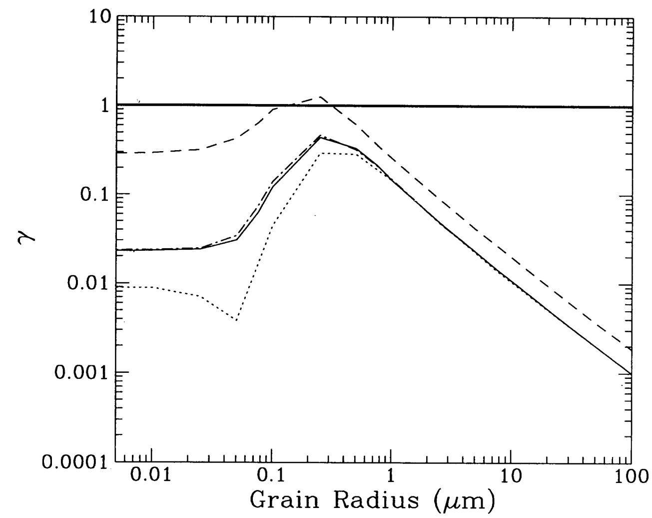

FIG. 5.—γ, the ratio of outward radiative force to the inward gravitational force, for grains of various radii. The solid line shows silicate grains with the properties published by Draine & Lee (1984); the dotted line shows the silicate described by Kratschmer & Huffman (1978); the dash-dotted line shows the silicate described by Day (1979); and the dashed line shows the amorphous carbon described by Hoare (1990). The heavy horizontal line at $\gamma = 1.0$ shows the threshold above which grains can be radiatively expelled from the stellar neighborhood.

The observation of a silicate feature at 9.7 μm in our CGS3 spectrum of SAO 26804 suggests that silicates ought to be the dominant species in the circumstellar disk, as would also be expected from knowledge of abundances of solid materials in the interstellar medium. We have adopted three silicate materials for use in our models: the "astronomical silicate" whose properties were presented by Draine & Lee (1984), the disordered olivine published by Kratschmer & Huffman (1978), and the amorphous $MgSiO_3$ measured by Day (1979) as used by Skinner & Whitmore (1987). We have also investigated the possibility that amorphous carbon grains might contribute to the IR excess, using the data for amorphous carbon due to Hoare (1990). In each case the dust data were calculated for each grain size using Mie theory from the published refractive indices.

It is not possible to fit the SED of SAO 26804 and the shapes of the CGS3 spectra with any size distribution of amorphous carbon or silicate grains. The FWHM of the silicate feature in SAO 26804 is $\sim$2.0 μm, which is slightly narrower than typical silicate features in evolved stars (e.g., the silicate features in M supergiants observed by Sylvester, Barlow, & Skinner 1994a typically had FWHM in the range 2.5–3.2 μm). The part of the CGS3 spectrum rising rapidly from 9 μm shortward toward 7.7 μm we attribute to the 7.7 μm PAH feature, and the rather narrow 9.7 μm silicate feature we attribute to very small, transiently heated silicate grains. In the next section we will show that with these assumptions it is possible to obtain a reasonable fit to the entire SED. For now we simply point out that the strength and narrowness of the silicate feature can only be fitted with a model of the type presented by SBJ if the grain

TABLE 2

MODEL RESULTS

Model	α	β	M_{disk} ($M_\odot$)	r_{in} (cm)	F25[a] (Jy)	F60[a] (Jy)	F100[a] (Jy)	r_{max} (μm)	f_{sil}	f_{ac}
IRAS PSC......	...	...	...	...	3.60 ± 0.22	7.60 ± 0.76	5.10 ± 0.51	...	...	...
M6A	2.0	2.5	1.3×10^{-7}	5.5×10^{13}	3.04 (0.90)	8.39 (0.99)	5.84 (1.02)	100	1.0	0.0
M6B	3.0	2.5	8.3×10^{-9}	5.5×10^{13}	4.33 (0.95)	2.73 (1.22)	0.67 (1.07)	100	1.0	0.0
M6C	2.0	2.5	7.5×10^{-9}	1.6×10^{13}	3.08 (0.99)	2.90 (1.10)	1.24 (1.04)	100	1.0	0.0
M7A	2.5	2.5	8.0×10^{-8}	2.0×10^{14}	3.46 (0.90)	5.15 (1.06)	2.92 (1.02)	100	0.0	1.0
M7B	2.5	1.8	1.2×10^{-7}	2.0×10^{14}	4.41 (0.90)	7.58 (1.05)	4.46 (1.02)	50	0.0	1.0
M7C	2.3	1.5	2.0×10^{-7}	2.0×10^{14}	3.69 (0.89)	8.16 (1.01)	5.61 (1.02)	25	0.0	1.0
M8A	2.5	2.4	2.4×10^{-7}	1.9×10^{14}	3.99 (0.88)	7.93 (1.03)	4.59 (1.03)	100	0.73	0.27
M9A	2.3	2.5	3.0×10^{-7}	1.6×10^{14}	3.28 (0.89)	7.33 (1.01)	5.20 (1.02)	100	0.74	0.26

[a] Number in parentheses is color correction to be applied at given wavelength.

population is dominated by small (submicron-sized) grains and that in such a model it is impossible to account for the strong far-IR fluxes (or low far-IR spectral index) with any plausible density distribution and resulting disk mass. The rapidly rising part of the spectrum shortward of 9 μm cannot be fitted with any combination of disk and grain parameters, and some alternative explanation such as PAHs is unavoidable.

We list details of some of the models we have constructed in Table 2 and display the listed models in Figures 6, 7, 8, and 11 (derived parameters are given in Table 3). We include in the table the simulated *IRAS* fluxes at 25, 60, and 100 μm and the color correction that should be applied at each wavelength (as we did in SBJ). The 12 μm flux and color correction are not included in this instance, as we felt to do so would not be instructive given the complications of the spectrum in the 10 μm region discussed above. We also include the total disk mass in the model, and the fractions by mass of silicate and amorphous carbon grains, f_{sil} and f_{ac}.

We present in Figure 6 models constructed using silicate dust grains. These models are listed in Table 2 as models M6A, M6B, and M6C. It can clearly be seen that no combination of parameters is able to fit the SED adequately. We can fit most of the 20 μm CGS3 spectrum, and the *IRAS* far-IR photometry, with models with $\alpha = 2.0$ and $\beta = 2.5$ and $d_{in} = 5.5 \times 10^{13}$ cm ($\sim$3 AU), i.e., M6A. If we significantly increase the value of α we obtain a strong 18 μm feature (M6B), inconsistent with the observed spectrum. A strong 9.7 μm feature is also obtained, which is very broad and quite different from the shape of the observed 9.7 μm feature. Somewhat smaller values of α are possible provided the value of β is increased to adjust the spectral index in the far-IR. The spectral index in the far-IR is extremely sensitive to the combination of α and β. We find that r_{max} must be close to 100 μm. A smaller value leads the model to fall below the *IRAS* 100 μm flux, while a larger value violates the 1100 μm upper limit. The value of d_{in} is very tightly constrained by the falloff in disk flux shortward of 18 μm. Thus we find that d_{in} and r_{max} are very well constrained by the observations, and α and β are well constrained in combination though not so well individually. We have attempted models using Kratschmer & Huffman (1978) and Day (1979) silicates, rather than that due to Draine & Lee (1984), and find very little difference. The Kratschmer & Huffman silicate produces slightly narrower features at 9.7 and 18 μm and produces more structure in the model spectra around 18 μm. The Day silicate likewise produces a narrow feature peaking at a somewhat shorter wavelength, around 9.5 μm, and the 18 μm feature is very similar to that produced by Draine & Lee's data. The disk masses and other parameters derived from the three sets of dust data are very similar, and the remainder of the models presented in this section all use the Draine & Lee data on the grounds that the short-wavelength data are better constructed in the Draine & Lee synthesis than in our synthesis from Kratschmer & Huffman's or Day's limited laboratory data.

TABLE 3

DERIVED PARAMETERS FOR SAO 26804 AND ITS DISK

Parameter	Value
Stellar radius	4.1×10^{10} cm
Stellar effective temperature	4500 K
Stellar luminosity	0.20 $L_\odot$
Distance	25 pc
Disk inner radius	1.6×10^{14} cm
Disk inclination	$\sim$75°
Disk mass	3.0×10^{-7} $M_\odot$
Fraction of disk by mass in:	
Silicate grains	74%
Amorphous carbon grains......	26%
Very small silicates	$\sim$0.2%
α	2.3
β	2.5
Maximum grain size	100 μm

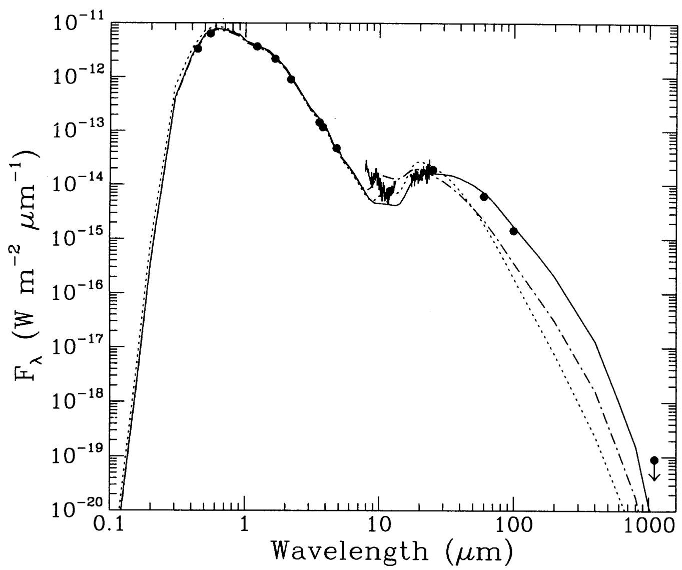

FIG. 6.—Models for the SED of SAO 26804 using only silicate dust grains. Models are summarized in Table 2 and are M6A (*solid line*), M6B (*dotted line*), and M6C (*dot-dashed line*).

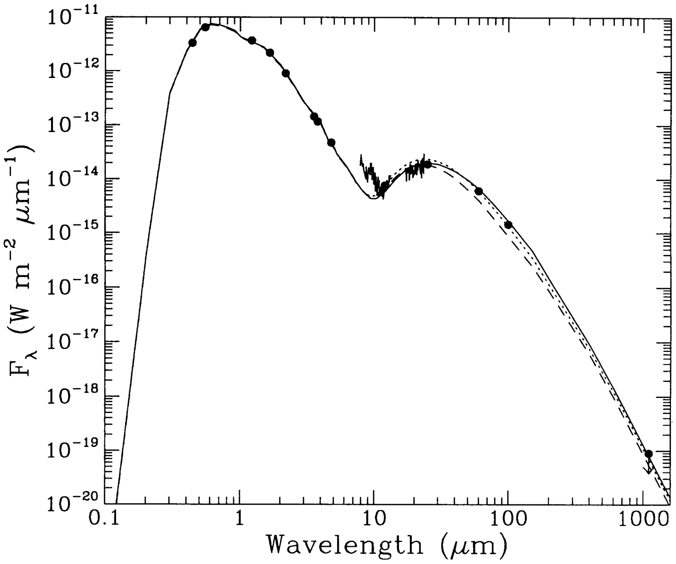

FIG. 7.—Models using amorphous carbon grains only. Again, details are listed in Table 2 for models M7A (*dashed line*), M7B (*dotted line*), and M7C (*solid line*).

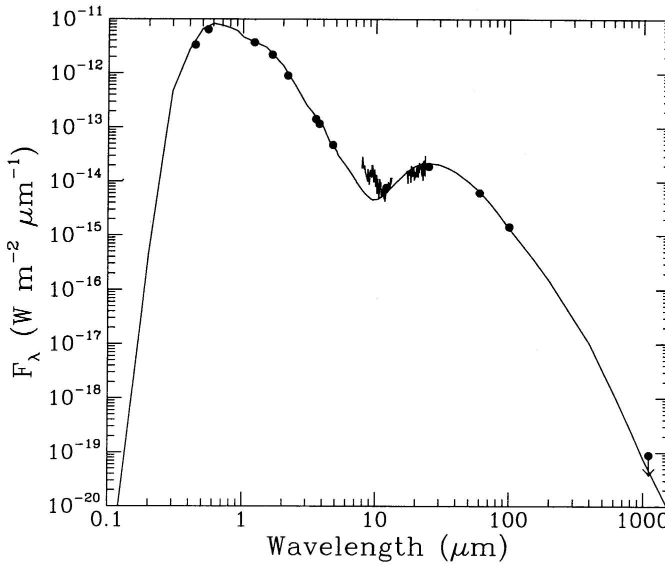

FIG. 8.—Model M8A, which uses a mixture of amorphous carbon and silicate dust.

Models constructed using amorphous carbon grains are presented in Figure 7 and listed in Table 2 as models M7A, M7B, and M7C. The same considerations apply to the choices of r_{max}, α, and β, except that now of course using too large a value for α does not create any undesirable spectral features. Because amorphous carbon is much more efficient at absorbing radiation than are silicates, the inner edge of the dust disk has to be moved further out, away from the central star, and we find $d_{in} = 2 \times 10^{14}$ cm. Lacking the strong mid-IR resonances of silicate dust, amorphous carbon is able to fit the rise in flux at the long-wavelength end of the 10 μm CGS3 spectrum. However, we are unable to simultaneously fit the 11–24 μm data *and* the far-IR data. If the spectral index is decreased in order to allow the model to fit the data at 11–24 μm and at 60 μm, then an excess in flux arises at 100 and 1100 μm. This can be corrected by reducing r_{max} to 25 μm and reducing the value of β. However, an undesirable side effect of reducing β is that the combined absorption efficiency of the grains now falls more rapidly with wavelength throughout the entire SED—this means that in the 11–13 μm region, where the observed spectrum rises very rapidly, the model spectrum now rises too slowly with increasing wavelength. Model M7C certainly presents the best fit of any single grain species model, but it would be problematic at best to try to fit the SED with large grains consisting only of amorphous carbon and small silicate grains. We therefore investigated mixed amorphous carbon and silicate models.

We present, in Figure 8, a model constructed using a mixture of amorphous carbon and silicate grains. The details are listed in Table 2 as model M8A. The dust in interstellar clouds is generally believed to contain a mixture of silicates and carbonaceous solids. For instance, Tielens & Allamandola (1987) suggest a ratio by mass of order 3:1 for O-rich:C-rich grains, where the O-rich grains are all silicates and the C-rich grains comprise some unknown mixture of PAHs, amorphous carbon, and graphite. Thus it would not be surprising to find a carbonaceous component in the disks around Vega-excess stars, given their presumed interstellar origin. We are now able to construct a model which fits all the data from 11 μm longward, in which the amorphous carbon grains dominate the emission in the 11–23 μm region and silicate grains contribute longward of this, and thus are able satisfactorily to fit the *IRAS* and JCMT data. The ratio of abundances by mass of silicate and amorphous carbon grains is entirely consistent with the aforementioned estimate for the interstellar medium.

3.3. *Small Grains*

The remarkably rapid rise in "continuum" flux at the short-wavelength end of the 10 μm CGS3 spectrum is suggestive of the presence of PAHs in this source. The 9.7 μm silicate feature also suggests the presence of small silicate grains. We define "small" here as being smaller than $\sim$50 Å in radius, which is the smallest size for which grains will remain more or less in equilibrium with the central radiation field. Smaller grains, because of their small heat capacity, are transiently heated by absorption of single photons with visible or UV wavelengths. Such grains therefore have a time-variable temperature and emission spectrum and so cannot be modeled using the simple code of SBJ.

We have adopted the technique of Guhathakurta & Draine (1989) to model small-grain emission in a circumstellar disk. The technique has been fully described by Guhathakurta & Draine. Here we will just briefly mention that the problem is solved by calculating the probability that a grain lies in a given temperature range and then integrating the emitted flux over all temperature bins weighted by the probabilities. We carry out this procedure at a grid of radial distances from the central star and sum the contributions over radius assuming some density distribution as described below.

We pointed out earlier that PRD will tend to remove very small grains from the disk, causing them to spiral inward toward the star. The timescale for this process is so short compared with the expected evolutionary timescale for such a system that the existence of small grains at all implies that they must be continuously produced in the disk, presumably by collisions between larger grains. We assume that these tiny grains share the radial density distribution of the larger grains in the disk. Interior to the inner edge of the disk we assume that the tiny grains spiral freely inward. If they were to fall in with a constant radial velocity, then geometry alone would now give us a radial density distribution $\rho_s \propto d^{-1}$. However, equation (1) tells us that the radial velocity increases as the grains approach the star, so that the velocity is proportional to d^{-1}. The combination of this with the aforementioned geometrical term leads to a constant density, independent of radius, interior to the disk. The grains do not spiral into the photosphere. Since they are so small, when they get fairly close to the star they will sublimate. We simply adopt the result of Guhathakurta & Draine (1989) that the grains will sublimate when their most probable temperature is in the region of 1700 K. The small-grain distribution is now completely specified, and the only unknown parameter is the total mass of small grains, to which the emitted spectral flux density is linearly proportional.

We have investigated the effects of the various adopted chromospheric line fluxes on the small-grain emission. At a given distance from the central star, we find that the most probable small-grain temperature is raised over that for a normal, or inactive, K dwarf by of order 10% by the UV line flux from a BY Draconis type star, and so the UV line flux does have a noticeable effect on the star-grain emission. As stated earlier, we have adopted a BY Draconis type chromosphere for all quoted results.

As in the case of the larger grains we have run models for the very small grains using each of the three possible sets of optical constants for silicate dust and for amorphous carbon. We show in Figure 9 the emission from systems containing each of the four types of dust, in each case the total mass of dust being $6.0 \times 10^{-10}\ M_\odot$. We have adopted a single grain size of 5 Å. Around a K dwarf, grains of much larger size, say 30 Å, do not fall far away from their equilibrium temperatures—there are too few photons of short enough wavelength to cause the grain temperatures to deviate strongly from equilibrium. On the other hand, silicate grains of 5 Å radius will have only $\sim$150 atoms or so (Guhathakurta & Draine 1989), and grains very much smaller than this may not behave much like solids at all.

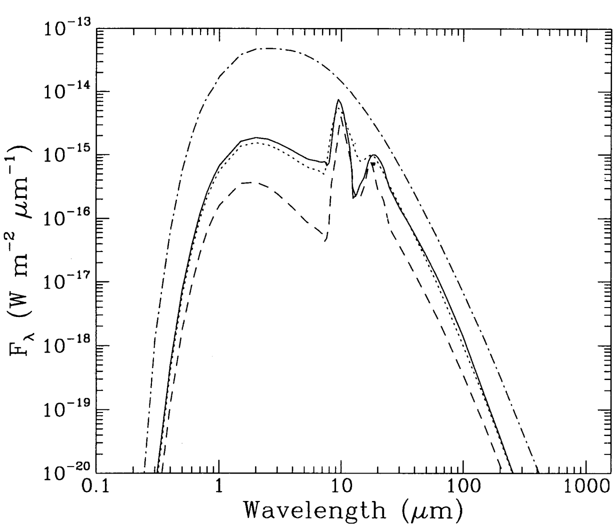

FIG. 9.—Small-grain models for the SAO 26804 disk. Models are presented using Day's silicate (*solid line*), Draine & Lee's silicate (*dotted line*), Kratschmer & Huffman's silicate (*dashed line*), and Hoare's amorphous carbon (*dash-dotted line*). In each case the total mass of small grains is $6 \times 10^{-10}\ M_\odot$.

Grains in the size range 5–15 Å behave very similarly to one another, the smaller grains typically being just a little hotter. For the silicates we find that the Kratschmer & Huffman grains have a feature of about the right width but peaking at rather too long a wavelength ($\sim$9.9 μm), Draine & Lee grains peaked closer to 9.5 μm but had too broad a feature, and the Day grains peaked at 9.5 μm and had about the right width when added to the composite large-grain model M9A (see Table 2). The mass of small Day silicate grains required to obtain a reasonable fit to the observed 10 μm spectrum is $\sim$0.2% of the total disk mass. As usual, because they are much more efficient absorbers, the same mass of small amorphous carbon grains greatly outshines the silicates at most wavelengths. Because our 10 μm spectrum is somewhat noisy, it is possible that the silicate feature is significantly stronger or weaker than we believe: in such a case the mass of very small grains which we have derived will be incorrect, but otherwise our results and conclusions will be unaffected.

The probability distribution for small Day silicate grains is presented in Figure 10. In the outer parts of the disk the most probable grain temperature settles at $\sim$15 K. The IR emission from these very cool grains is negligible, and we can be sure that our model has included all the significant grain emission.

We do not attempt to model the PAH emission in this source. Some crude numerical models of PAH emission have been developed in the past couple of years (e.g., Schutte, Tielens, & Allamandola, 1993), but the details of these are still very poorly determined, and we believe such a model for this source is unjustified in view of the many other uncertainties in our knowledge of this system. Instead we have adopted an SED for the PAH contribution, based largely on observations of the C-rich protoplanetary nebula IRAS 21282+5050 presented by Roche, Aitken, & Smith (1991) and by Buss et al. (1993), and simply added this to our model in order to demonstrate the feasibility of PAHs as an explanation of the 8 μm excess in the CGS3 spectrum. The adopted PAH spectrum is displayed in Figure 11*c*.

The SED generated by the composite model containing both small and large silicate grains, large amorphous carbon grains, and PAHs is presented in Figure 11. All of the principal features of the observed SED are successfully reproduced by our model, though there is room for improvement in a few areas. The fit in the 11–13 μm region is still not as good as we might hope. The 9.7 μm silicate feature is still too broad even though we have used Day's data, which yield the narrowest of the available silicate features. In fact it probably should not surprise us that optical constants derived for silicate particles many microns in radius do not provide a good fit for grains containing only a few tens of hundreds of atoms. If the 9.7 μm silicate feature were made significantly narrower so that the small silicate grains provided negligible flux in the 11–15 μm region between the two silicate resonance features, then our large-grain model M8A could be used in the composite model, providing a better fit to the rapidly rising continuum in the 11–13 μm portion of the CGS3 spectrum. The fit to the *IRAS* data and to the 20 μm CGS3 spectrum are all good, and the model 1100 μm flux of 15 mJy is well below our 36 mJy upper limit.

3.4. *Spatial Structure*

In our model we have basically three spatially distinct elements at 10 μm—the star, the innner small-grain population, and the disk containing both small and large grains. The star of

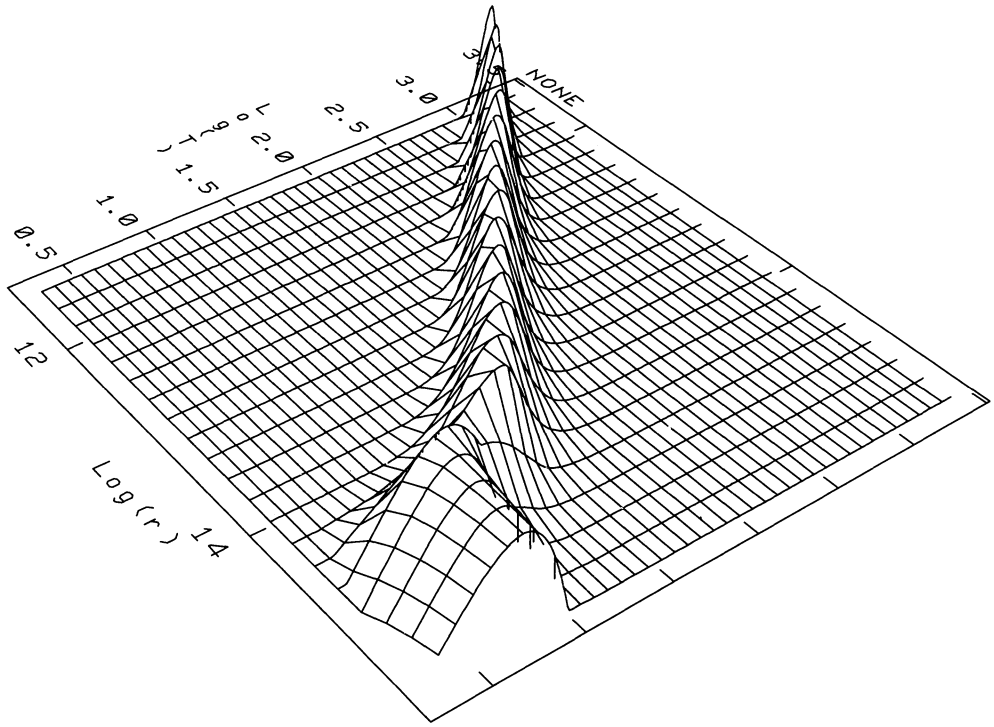

FIG. 10.—Probability of a grain having a given temperature (T, in thousands of kelvins) as a function of distance from the star (r, in centimeters)

course is a point source, but the spatial information provided by our N = band image of the SAO 26804 disk may help to clarify the relative contributions of small and large grains to the mid-IR emission. An N-band surface brightness profile along the major axis of the model disk is presented in Figure 12*a*, and its convolution with a Gaussian profile of FWHM 1″.1 in Figure 12*c*. The small, hot grains very close to the star dominate the small-grain component, which is to all intents and purposes a point source. The disk is, however, extended on a scale that is consistent with our image—we show the convolution of the large-grain model only, with no small grains, in Figure 12*b*. This model when convolved with a 1″.1 Gaussian gives a FWHM on the major axis of 1″.45, just a little smaller than our observed value of 1″.5.

Our composite model, while it provides a good representation of the SED of the system, does not fit the spatial information well. The FWHM of the large disk alone is almost as large as that of the observed disk at 10 μm, indicating that our derived dimensions for the large-grain component are probably fairly accurate. But our small-grain model is less satisfactory. If we were to increase significantly the photon flux at short (i.e., X-ray or UV) wavelengths the small-grain component could be more efficiently heated at greater distance from the star, and a large enough increase could add to the dimensions of the large-grain disk also. We discuss this possibility further in the next section.

We have run our models assuming a disk inclination angle of 75°. Our failure to resolve the disk at all on its minor axis suggests that the disk cannot be inclined much more than $\sim$30° away from edge-on. Our model yields integrated fluxes of 0.17 Jy for the small-grain component, 0.08 Jy from the large-grain component, and 0.08 Jy from the stellar photosphere, at 10 μm (through an N-band filter, covering the 8–12 μm wave band). Thus the small grains are providing two-thirds of the IR excess at this wavelength.

Interestingly, at 10 μm we find that $\sim$2% of the total observed flux is scattered. This would be tantalizingly close to providing observable polarization of the emission, and indeed 1% polarization should be detected with an array camera with polarization imaging capability. Such a large scattering polarization at 10 μm is possible in these sources because of the very large grains present in the disks, which are able to efficiently scatter at mid-IR wavelengths, unlike the rather small grains typically present in sources such as moleclar clouds or asymptotic giant branch stars. At visible wavelengths in our model, $\sim$10% of the total flux is scattered. Since this is scattered over a large area (the approximate area of the disk is 300 arcsec^2), the scattered surface brightness should not be particularly bright, but this should be detectable. However, because the central star is so bright, it is probably necessary to use a coronagraph to detect the scattered component.

4. DISCUSSION

Given the complexity of this model, the question of whether it is unique will arise at once. In practice most elements of the model are quite strongly constrained. The values of α and β in the disk are constrained to lie within $\pm$10% or so of our listed values given the values assigned to other parameters, otherwise the model spectral index in the mid- and far-IR disagrees substantially with the observations. Similarly, if we change r_{max} significantly, we move the turnover of the SED and may violate the 1100 μm upper limit and obtain a poor fit to the far-IR spectral index. The combination of d_{in} and the mass of small grains critically affects the shape of the continuum in the 11–20 μm region, and any variation of their parameter significantly worsens the fit to the data. Basically all the large-grain model parameters are interconnected, and a change to any one parameter requires changes to a sequence of other parameters in order to regain some kind of fit to the data, and whatever the change, the resulting fit to the data is inferior in at least one

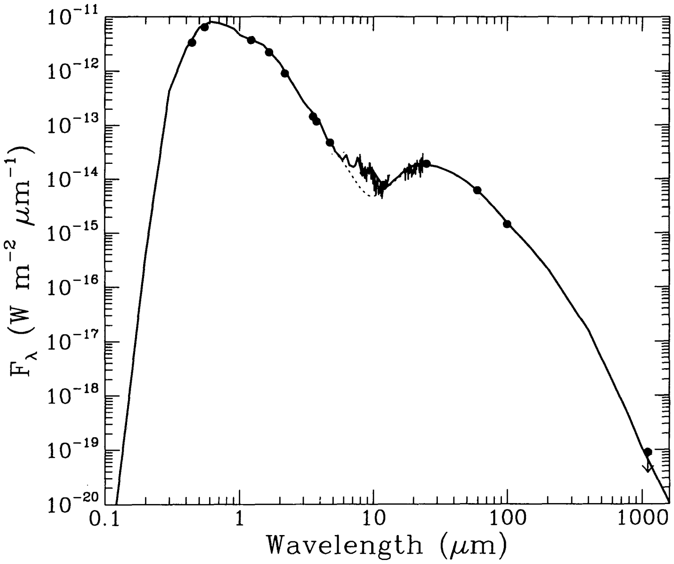

FIG. 11*a*

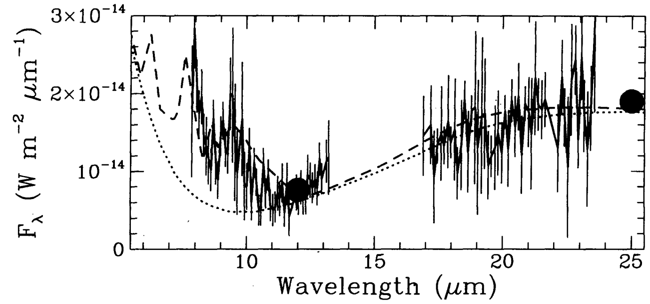

FIG. 11*b*

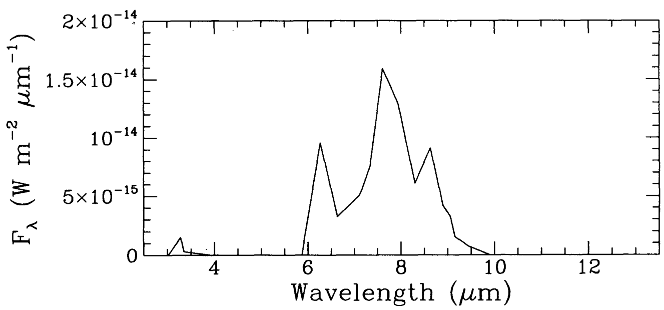

FIG. 11*c*

FIG. 11.—(*a*) Composite model for the SAO 26804 disk (*solid line*), including a "large" silicate plus amorphous carbon disk model (*dotted line*), the small-grain model using Day's silicate, and a simulated PAH spectrum which is shown separately in (*c*). The mid-IR region is shown expanded in (*b*), with the observed spectrum indicated with a solid line and error bars, the composite model with a dashed line, and the "large" grain only model with a dotted line. *IRAS* fluxes are shown as filled circles, whose radii are roughly the size of the uncertainties.

respect to that from the model presented here as M9A. Thus we believe all of the parameters in the large-grain model are adequately constrained by the observations, just as we found in our models of SAO 179815 (SBJ).

The same cannot be said of the small-grain model. What must be beyond doubt is that small grains do make a substantial contribution to the observed spectrum in the 10 μm region. Our model demonstrates convincingly that PAHs can account very well for the rapidly rising continuum shortward of 9 μm. We can find no other explanation for this characteristic of the observed spectrum. The absence of any discernible 11.3 μm PAH feature in the CGS3 spectrum is a little unusual given the strength of the 7.7 μm feature, but not unprecedented among well-known sources with PAH features: R CrB, for instance, seems to have a distinct PAH feature in the 7–9 μm region, but has no discernible 11.3 μm feature, and the same appears to be true of the Cygnus Egg Nebula (Buss et al. 1993). More importantly, another Vega-excess star, SAO 186777, displays a very prominent 7.7 μm PAH feature and a rather weak 11.3 μm feature (Sylvester, Barlow, & Skinner 1995)—so weak that if the band strength ratio were repeated in SAO 26804 we would not see the 11.3 μm feature above the noise. Our model clearly shows that small, transiently heated silicate grains can explain the fairly narrow 9.7 μm feature in SAO 26804, and once again we can find no other means of explaining this.

The numerical details of our small-grain model are very poorly constrained. Our first problem here is that the nature of the stellar radiation field at UV (and shorter) wavelengths is very poorly known. In the optical and near-IR our assumed Kurucz (1991) stellar model-atmosphere spectrum fits the photometry very well, confirming incidentally that the star is not significantly reddened. In the UV, however, where many (perhaps most) of the photons responsible for small-grain heating are produced, the stellar radiation field is unconstrained. The continuum is probably very weak, but the continua of BY Draconis stars might be enhanced by an order of magnitude or more above those of normal K dwarfs, and *IUE* would still not detect them. Such an increase in the UV continuum flux would increase the heating rates for small grains substantially, and probably have some discernible effect on the large-grain heating also, and so affect our models. For the case of this particular star, the chromospheric line fluxes are unknown. We understand that BY Draconis stars probably have significantly enhanced UV line fluxes, but *how* enhanced is poorly known. We have simply adopted the parameters for HD 36705 (Rucinski 1985) as the best "guesstimate" we could make currently. It is possible that future UV observations will help to settle this question. Just to worsen the picture, we note that active stars such as ϵ Eri are often found to be significant soft X-ray sources (e.g., Linsky et al. 1982). The absorption efficiency of astronomical silicates in this wave band is entirely unknown, but it is likely (e.g., Laor & Draine 1993) that significant X-ray photon rates would have a noticeable effect on small-grain heating rates. Thus it is possible that we have overestimated the small-grain temperatures (by at most ~10%), but it is also possible that we have underestimated them by significantly more. It is to be hoped that time will tell.

Even if we have made a good estimate of the stellar radiation field at all wavelengths, it is quite likely that our assumed density distribution for the small grains is a gross oversimplification, and possible that it is completely wrong. Vega-excess stars with large IR excesses such as SAO 26804, must rank among the most likely stars to possess planetary systems. The inner radius we deduce for the SAO 26804 dust disk, close to 10 AU, is quite consistent with the size for a region that one might expect to be cleared of dust grains by a young planetary system (as postulated by Marsh & Mahoney 1993 for a few T Tauri stars). Small grains spiraling toward the central star under the influence of PRD would probably, in such a system,

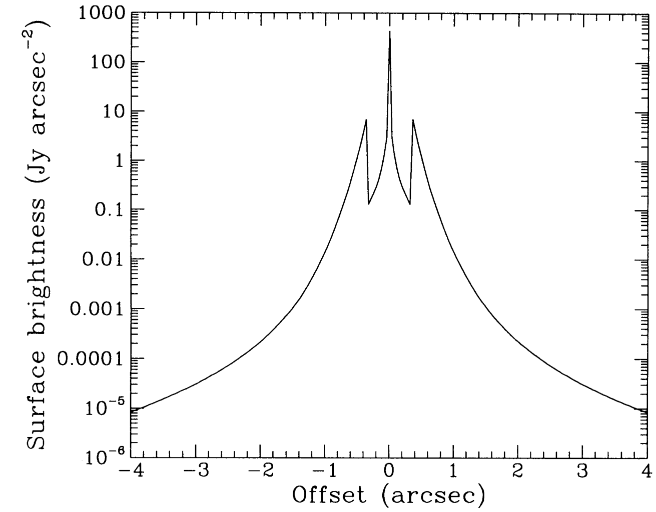

FIG. 12*a*

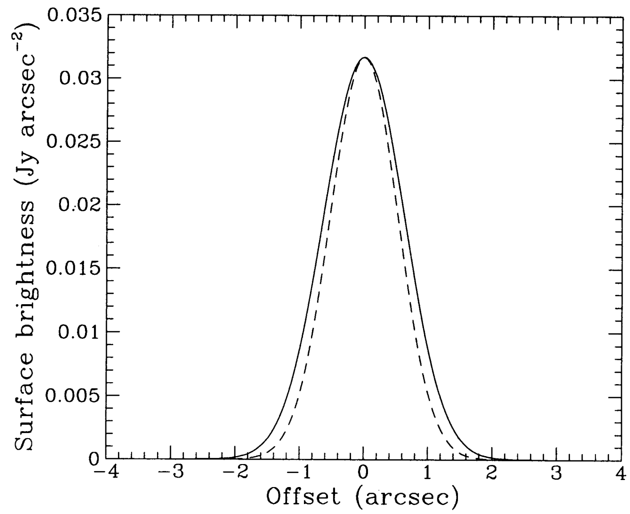

FIG. 12*b*

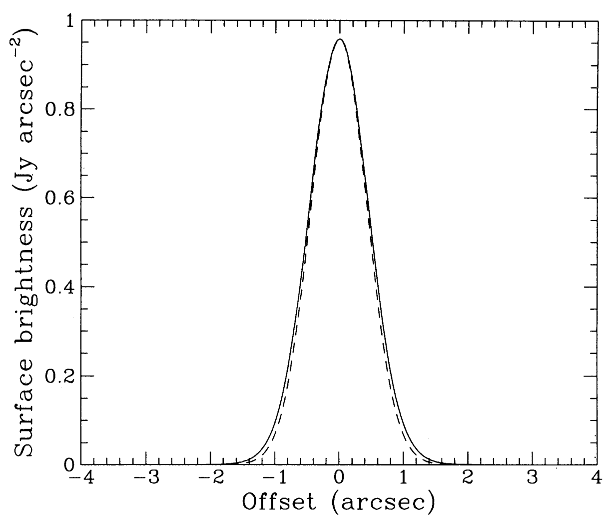

FIG. 12*c*

FIG. 12.—*N*-band surface brightness profile along the major axis of the composite model shown in Fig. 11*a*. The sharp central spike is mostly due to the stellar photosphere, the broader pedestal beneath it is due to the small-grain component, and the two spikes separated by ~0".8 are due to the large grains. (*b*) As (*a*), but for the large-grain component only, convolved with a circular Gaussian seeing disk with FWHM 1".1: the solid line is the profile along the major axis, and the dashed line that along the minor axis, where the disk is basically unresolved. (*c*) As (*b*), but for the composite model shown in (*a*) convolved with a 1".1 seeing disk Because of the large contributions from the pointlike small-grain distribution and the stellar photosphere, the model is basically unresolved, and the profiles along the two axes are nearly identical.

not simply spiral freely in toward the star. Some of them may be swallowed by planets or planetesimals, and many may be shepherded into preferred orbits by tidal effects in the planetary system. Our assumption of uniform density in this inner region is thus probably a very optimistic one, but given the extent of our knowledge of the SAO 26804 system it is pointless to investigate anything more complicated.

The comparison of our model with the *N*-band image suggests that there may indeed be a substantial short-wavelength excess in SAO 26804. In the fairly active K dwarf ϵ Eri, the soft X-ray flux is ~10 times larger than the sum of all the UV chromospheric line flux. If this were repeated in SAO 26804, we could expect the inner radius of the large-grain disk to expand by ~10%, and the distribution of small grain flux to extend outward dramatically. Recent observations of the young K0 V star HD 197890 (also known as "speedy Mic") show that its UV continuum (Robinson et al. 1994) is more than an order of magnitude brighter than that of a normal K dwarf. If SAO 26804 had a UV continuum as bright as that of Speedy Mic, again the effect on the surface brightness distribution would be substantial. Thus there are ample grounds for believing that excess short-wavelength emission in SAO 26804 may rectify the spatial discrepancy between our model and observations. Finally, the distribution of the PAH emission is entirely unknown, and this will have some effect on the spatial structure of our model. Thus given future observations of SAO 26804 at short wavelengths, it is possible that our models could be made quite consistent with the observed spatial extent of the disk at 10 μm.

The matter of the ratio of abundances of small silicate grains, small amorphous carbon grains, and PAHs is of interest. From the models presented in Figure 9 it is evident that the ratio of silicate to amorphous carbon in the small-grain population is probably quite large. In fact, from the lack of any detectable excess in the *M* band, we estimate that amorphous carbon accounts for at most 10% (by mass) of the small grains. However, PAHs appear to be responsible for a very strong feature at 7.7 μm and so presumably may represent a significant fraction of the total mass of small grains. We could therefore speculate that if the large amorphous carbon grains are to some extent hydrogenated, then the very small amorphous carbon grains generated, like the small silicate grains, by collisions between larger grains) in fact *are* PAHs, and hence the question addressed above of the fractional abundance of very small amorphous carbon grains is an inappropriate one. The appearance of the narrow PAH features is then a function of the degree to which the functional units in the grain or cluster (the aromatic rings and attached hydrogen atoms or aliphatic side groups) are able to operate as individual molecular groups, rather than being suppressed and overwhelmed by the bulk grain properties as in the larger amorphous carbon (or hydrogenated amorphous carbon [HAC]) grains.

We can make a crude investigation of the mass of PAH molecules required to explain our 7.7 μm feature using data from Schutte et al. (1993). They quote an integrated cross section for the 7.7 μm feature of 2.0×10^{-21} cm^2 μm per C atom, from which we derive an Einstein *A*-coefficient of 0.447 s^{-1}. The integrated intensity of our 7.7 μm feature is $\sim 7.2 \times 10^{-12}$ ergs cm^{-2} s^{-1}, and thus we derive a total number of C atoms in excited PAH molecules of $\sim 3 \times 10^{43}$. If every PAH molecule were permanently excited we would then have a mass of $\sim 3 \times 10^{-13}$ $M_\odot$ of PAHs in the disk. Of course, there is only some finite probability that each PAH molecule will be excited at any given time, which is dependent on the photon rate throughout the disk. Schutte et al. suggest that only photons with wavelengths shorter than 5000 Å will efficiently excite PAHs, and at the surface of our star we calculate a photon flux in this wavelength range of $\sim 5 \times 10^{20}$ s^{-1} cm^{-2}. At the radius at which we find small silicate grains are likely to be sublimated (2×10^{11} cm), the photon flux is $\sim 2 \times 10^{19}$ s^{-1} cm^{-2}, while at the inner edge of the disk (1.6×10^{14} cm), where the small silicate grains emit at a negligible rate, the photon flux is still 2×10^{13} s^{-1} cm^{-2}, which is comparable to that in the Orion bar region, where for typical PAHs containing a few hundred C atoms the probability of a PAH being excited is about one-tenth (from Schutte et al. 1993). However, the photons in the neighborhood of the Orion are very much more energetic on the whole than those emitted by SAO 26804. By this means we can crudely estimate that, in the region closer to the star than $\sim 5 \times 10^{13}$ cm, PAHs probably absorb more than one photon per relaxation time and thus exist more or less in temperature equilibrium. Farther from the star than this, the PAHs are no longer in equilibrium, and the probability that a given PAH is in an excited state drops rapidly. In this region, the PAHs are occasionally heated by the absorption of a single photon and subsequently radiate strongly in the well-known IR bands, but for a substantial fraction of the time they are rather cold and emit very little. Finally, we have the very crude estimate that the total mass of PAHs in the disk is of order 3×10^{-11} $M_\odot$, which is $\sim 5\%$ of the mass of very small silicate grains. Given the gross approximations in this derivation, we can certainly conclude that it is consistent with as much as 25% of the mass of very small grains being in the form of PAHs, and given the photon fluxes we calculate it is not surprising that PAH features are seen in this source. This calculation is probably only accurate to an order of magnitude or so even if we believe the stellar radiation field we have used, and as discussed earlier there is a significant chance that the stellar radiation field we have used may underestimate the important photon flux at short wavelengths. However, it is nonetheless a calculation which can give us some confidence that the invocation of PAHs to explain part of the mid-IR excess is reasonable.

Our conclusion that amorphous carbon grains must be present in the SAO 26804 disk is one that has not been previously considered for Vega-excess stars, but probably should have been. As discussed by us earlier, in the interstellar medium we expect that of order 25% of the refractory grains are carbonaceous, and one might expect such a ratio to prevail in the Vega-excess disks that are born in the interstellar medium. Because the mid-IR spectra of Vega-excess stars that have been published so far have all shown silicate features, these systems have generally been treated as though they contained silicate dust and only silicate dust. However, Sylvester et al. (1995) present spectra which show that things are certainly not this desirably simple. Aitken et al. (1993) report that the continuum underlying the weak silicate feature in β Pic can be fitted with a 725 K blackbody continuum. One might ask why an A star with a 9000 K effective temperature should produce a 725 K blackbody continuum at 10 μm. This is in fact about twice the temperature derived by Aitken et al. (1993) for the silicate grain component, and we find that in the radiation field of an A star amorphous carbon grains at a given distance from the star reach an equilibrium temperature about twice that for silicate grains. It is clear that the SEDs of young systems with disks should be modeled with caution: the presence of a silicate feature does not immediately preclude the presence of carbonaceous grains in the same system, and in fact it would be surprising if both types of grain were not *usually* present. Because they are so much more efficient absorbers, amorphous carbon grains will have a tendency to dominate IR excesses of many of these systems except in the neighborhood of the mid-IR silicate features, even for a much greater abundance of silicates.

In the light of this, it would be worthwhile to reconsider our own previously published model of the disk around SAO 179815. Given the strong PAH emission we see in the SAO 26804 10 μm spectrum, and the lack of any PAH emission in the SAO 179815 spectrum, we might infer that SAO 26804 may be an even younger system than SAO 179815 and thus more chromospherically active. The fractional IR excess is a little lower than that for SAO 179815: we determine $L_{IR}/L_* = 0.036$ for SAO 26804, which is a little less than half that of SAO 179815. However, the latter is a multiple-star system, and if we accept the luminosity calculated for the primary star by Zuckerman & Becklin, then its fractional IR excess is instead 0.17. Nonetheless, SAO 26804 has a very large IR excess and we hope that it will receive as much observational attention as SAO 179815 has recently.

Finally, the detection of numerous young stars in the solar neighborhood deserves some comment. Fekel & Bopp (1993) and Gregorio-Hetem et al. (1992) note that SAO 179815 may have just recently emerged from the T Tauri phase and that it lies only 10° away from TW Hya, another isolated T Tauri star. On this basis Fekel & Bopp suggest that these two stars may be a remnant of a small, recently formed association. SAO 26804 is much farther away on the sky from either star, and β Pic lies almost is the opposite direction. β Pic is another extremely young star, albeit a rather more massive one. All of these stars lie within 25 pc of the solar system and surround us. We thus suggest that, rather than representing a nearby association, these stars may in fact be part of one newly formed association, through which the Sun is currently passing. Such an association would have to be several tens of parsecs across, which would make it much larger than, say, the Chameleon or Ophiucus star-forming regions, comparable with the present size of the Taurus dark cloud, and much smaller than the association forming in the Gum Nebula. In such a case there may be more very young stars with significant IR excesses waiting to be discovered very close to the solar system. We would then be in a very fortunate position, having the opportunity to get a close-up look at a number of very young stars, whose protoplanetary debris disks have large enough angular scale to be resolved at many wavelengths.

5. CONCLUSIONS

We present multiwavelength observations, from near-IR to millimeter wavelengths, of the Vega-excess star SAO 26804, including the first resolved image of a Vega-excess star disk other than β Pic. We have constructed a model disk which fits the spectral energy distribution for the star throughout the wavelength region from the V band to 1.1 mm. The mass of the circumstellar disk according to our model is $3.0 \times 10^{-7}\ M_{\odot}$. The model indicates that the disk contains grains with a distribution of sizes ranging from 5 Å up to $\sim 100\ \mu$m and that there are both silicates and carbonaceous grains in the disk. We find that the 10 μm spectrum is dominated by the emission from very small grains which are transiently heated by absorption of single photons, including both very small silicate grains and PAHs. The ratio of abundances by mass for the silicate and carbonaceous grains is consistent with that determined for the interstellar medium. Our model underestimates the spatial extent of the disk: this we suggest could be due to the star having a significant excess flux in the UV and/or X-ray region for which we have not accounted, possibly because the star is very young and hence has considerable surface activity.

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REFERENCES

Aitken, D. K., Moore, T. J. T., Roche, P. F., Smith, C. H., & Wright, C. M. 1993, MNRAS, 265, L41
Artymowicz, P. 1988, ApJ, 335, L79
Artymowicz, P., Burrows, C., & Paresce, F. 1989, ApJ, 337, 494
Aumann, H. H. 1985, PASP, 97, 885
Aumann, H. H., et al. 1984, ApJ, 278, L23
Ayres, T. R., Marstad, N. C., & Linsky, J. L. 1981, ApJ, 247, 545
Backman, D. E., & Paresce, F. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. Arizona Press), 1253
Becklin, E. E., & Zuckerman, B. 1990 in Submillimetre Astronomy, ed. G. D. Watt & A. S. Webster (Dordrecht: Kluwer), 147
Burns, J., Lamy, P. L., & Soter, S. 1979, Icarus, 40, 1
Buss, R. H., Tielens, A. G. G. M., Cohen, M., Werner, M. W., Bregman, J. D., & Witteborn, F. C. 1993, ApJ, 414, 250
Day, K. L. 1979, ApJ, 234, 158
Draine, B. T., & Lee, H-M. 1984, ApJ, 285, 89
Duncan, W. D., Robson, E. I., Ade, P. A. R., Griffin, M. J., & Sandell, G. 1990, MNRAS, 243, 126
Fekel, F. C., & Bopp, B. W. 1993, ApJ, 419, L89
Fekel, F. C., Bopp, B. W., Africano, J. L., Goodrich, B. D., Palmer, L., Quigley, R., & Simon, T. 1988, AJ, 92, 1150
Gillett, F. C. 1986, in Light on Dark Matter, ed. F. P. Israel (Dordrecht: Reidel), 61
Gregorio-Hetem, J., Lepine, J. R. D., Quast, G. R., Torres, C. A. O., & de la Reza, R. 1992, AJ, 103, 549
Guhathakurta, P., & Draine, B. T. 1989, ApJ, 345, 235
Hildebrand, R. H. 1983, QJRAS, 24, 267
Hoare, M. G. 1990, MNRAS, 244, 193
Keto, E., Jernigan, J. G., Ball, J. R., Arens, J. F., & Meixner, M. 1991, ApJ, 374, L29
Knacke, R. S., Fajardo-Acosta, S. B., Telesco, C. M., Hackwell, J. A., Lynch, D. K., & Russell, R. W. 1993, ApJ, 418, 440
Kratschmer, W., & Huffman, D. R. 1978, Ap&SS, 61, 195
Kurucz, R. L. 1991, in Precision Photometry: Astrophysics of the Galaxy, ed. A. G. Davis Philip, A. R. Upgren, & K. A. Janes (Schenectady: Davis), 27
Lagage, P. O., & Pantin, E. 1994, Messenger, 75, 24
Laor, A., & Draine, B. T. 1993, ApJ, 402, 441
Linsky, J. L., Bornmann, P. L., Carpenter, K. G., Wing, R. F., Giampapa, M. S., Worden, S. P., & Hege, E. K. 1982, ApJ, 260, 670
Marsh, K. A., & Mahoney, M. J. 1993, ApJ, 405, L71
Mathis, J. S., Rumpl, W., & Nordsieck, K. H. 1977, ApJ, 217, 425
Paresce, F., & Burrows, C. 1987, ApJ, 319, L23
Robinson, R. D., Carpenter, K. G., Slee, O. B., Nelson, G. J., & Stewart, R. T. 1994, MNRAS, 267, 918
Roche, P. F., Aitken, D. K., & Smith, C. H. 1991, MNRAS, 252, 282
Rucinski, S. M. 1985, MNRAS, 215, 591
Schutte, W. A., Tielens, A. G. G. M., & Allamandola, L. J. 1993, ApJ, 415, 397
Skinner, C. J. 1994, MNRAS, 271, 300
Skinner, C. J., Barlow, M. J., & Justtanont, K. 1992, MNRAS, 255, 31 (SBJ)
Skinner, C. J., & Whitmore, B. 1987, MNRAS, 224, 335
Smith, B. A., & Terrile, R. J. 1984, Science, 226, 1421
Sylvester, R. J., Barlow, M. J., & Skinner, C. J. 1992, in Dusty Discs, ed. P. M. Gondhalekar (RAL Int. Rep RL92-082), 172
———. 1994a, MNRAS, 266, 640
———. 1994b, in Planetary Systems: Formation, Evolution and Detection, ed. B. F. Burke, J. Rahe, & E. E. Roettger (Dordrecht: Kluwer), in press
———. 1995, in preparation
Telesco, C. M., Becklin, E. E., Wolstencroft, R. D., & Decher, R. 1988, Nature, 335, 51
Telesco, C. M., & Knacke, R. S. 1991, ApJ, 372, L29
Tielens, A. G. G. M., & Allamandola, L. J. 1987, in Interstellar Processes, ed. D. J. Hollenbach & H. A. Thronson (Dordrecht: Reidel), 397
Walker, H. J., & Wolstencroft, R. D. 1988, PASP, 100, 1509
Zuckerman, B., & Becklin, E. E. 1993, ApJ, 406, L25

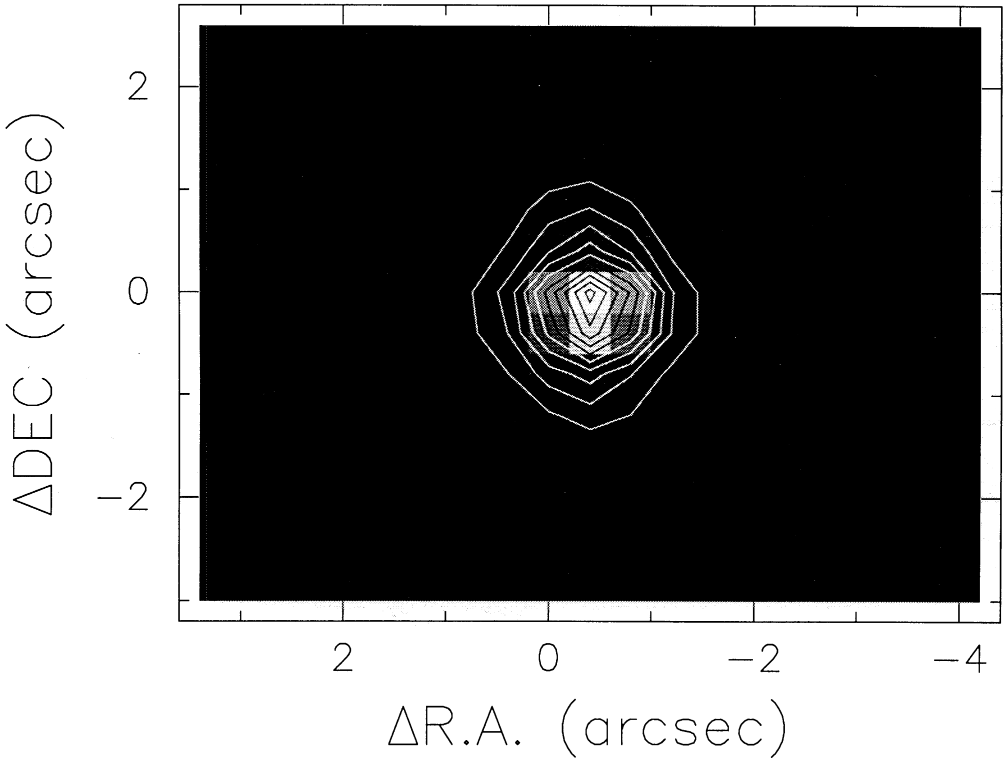

FIG. 3*a*

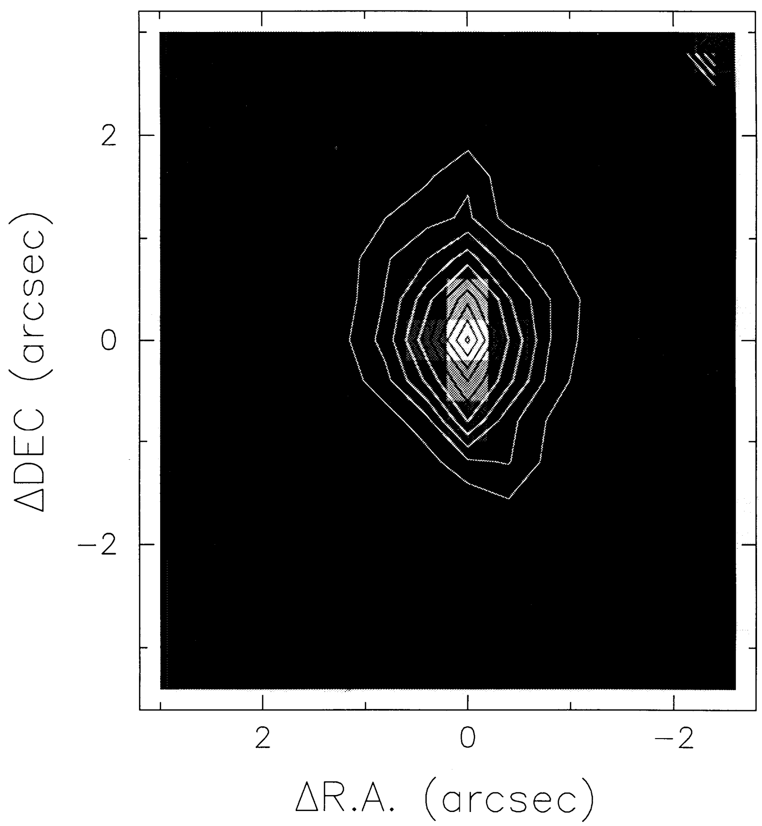

FIG. 3*b*

FIG. 3.—*N*-band images of (*a*) the point source calibrator β Gem (contour levels linearly spaced from a peak level of 60 Jy arcsec^{-2} to 5% of the peak) and (*b*) SAO 26804 (again levels linearly spaced from a peak of 0.17 Jy arcsec^{-2} down to 5% of the peak).

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