FAR-INFRARED CONSTRAINTS ON DUST SHELLS AROUND VEGA-LIKE STARS

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ABSTRACT

We present results of observations at 47 and 95 μm from the Kuiper Airborne Observatory of several "Vega-like" stars. Spatial cuts and aperture photometry are presented for β Pictoris and Fomalhaut, and for HD 135344, HD 139614, HD 142527, and HD 169142, four stars that had been suggested to possibly represent more distant examples of the Vega phenomenon by Walker & Wolkstencroft. We have modeled the dust around β Pic and Fomalhaut with a spatially and optically thin disk to determine the constraints our new observations place on the properties of the dust disks that are required to explain the infrared and optical properties of these two stars. For β Pic we find that models similar to those proposed by Backman, Gillett, & Witteborn can fit our data quite well. For Fomalhaut we find that very different models are required which have much "blackter" dust with a much shallower density distribution, surface density $\propto r^{-0.5}$, than for β Pic. Our observations of the four HD stars are consistent with their being spatially unresolved. Because of their distance, this does not allow us to put any new constraints on their circumstellar shells.

Subject headings: circumstellar matter — dust, extinction — infrared: stars

1. INTRODUCTION

One of the most exciting and unexpected discoveries made by the IRAS survey was that of thermal dust emission from main-sequence stars, the "Vega" phenomenon (Aumann et al. 1984; Gillett 1986). Not only was dust unexpected around main-sequence stars that were not undergoing detectable mass loss, but the cloud sizes and temperatures indicated that the particles must be much larger than typical interstellar grains. Furthermore, estimates of the lifetimes of such grains against radiation pressure and the Poynting-Robertson effect showed that the 10–100 μm diameter grains probably had to be constantly replenished from a reservoir of, perhaps, much larger grains. Unfortunately, the spatial resolution of IRAS in the far-infrared, where these clouds are most luminous, was barely sufficient to resolve them. Therefore, the constraints on the dust properties due to the spatial extent of the clouds were not completely defined.

Immediately after the announcement of this discovery, the Kuiper Airborne Observatory (KAO) was used both to make confirming observations of the phenomenon and to supply additional spatial and spectral constraints on the emission (Harvey, Wilking, & Joy 1984, hereafter HWJ; Harper, Loewenstein, & Davidson 1984). These results, as well as a recent reanalysis of the HWJ data (van der Bliek, Prusti, & Waters 1994), showed the value of the substantially higher spatial resolution possible with the KAO, even though its sensitivity is much poorer than that of IRAS.

For the past half-dozen years we have been attempting to obtain the highest possible quality new observations of several of these objects with the KAO. Since the largest fraction of them lie at southern declinations, this has involved the use of the KAO on its regular deployments to New Zealand, which began with the appearance of SN 1987A. In this paper we report the results of these observations and discuss their implications for the properties of the circumstellar clouds around the observed stars. Our most complete data are on β Pic and Fomalhaut (α Piscis Austrini). In addition, we have obtained some observations on four stars that were suggested by Walker & Wolkstencroft (1988) to have properties similar to the four original stars found by IRAS. In the following sections of this paper we discuss the details of our observations, the basic observational results, simple models that can fit most of the observational data on β Pic and Fomalhaut, and constraints on the dust shells around the additional stars.

2. OBSERVATIONS

All the observations presented here were made on the KAO flying out of Christchurch, New Zealand, between 1988 and 1994, with one of two detector systems. The first system consisted of an array of 1 × 8 bolometers imaged on the focal plane with a pixel scale of roughly $\lambda/2D \times \lambda/D$ at effective wavelengths of either 47 or 95 μm ($\lambda/\Delta\lambda \sim 1.5$) (Smith et al. 1991). The second system used the same optics, filtering, and pixel scale, with a 2 × 10 array of bolometers (Smith et al. 1994). The details of the observations, including dates, calibration objects, detector system used, wavelengths, and objects observed are given in Table 1. Also shown in Table 1 is the rotational orientation of the sky relative to the detector arrays; for these angles the convention is that the long axis of each array was along the 0°–180° line, and the angle indicated is that by which the sky was apparently rotated from north (0°) through west (90°). All of the observed objects are bright, visible stars, so no off-axis guiding was required. The absolute calibrations are believed accurate to ±15%, except in the case of the 1992 data, where the large number and consistency of calibration sources give calibration uncertainties of ±10%.

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### TABLE 1

| Date        | Calibrator | Detectors | $\lambda$ (\(\mu\)m) | Star       | Field Rotation (deg) |
|-------------|------------|-----------|-----------------------|------------|----------------------|
| 1988 Nov    | Ceres, $\eta$ Car | 1 $\times$ 8 | 95 | $\beta$ Pic | 290 |
|             |            |           | 95 | Fomalhaut | 125 |
| 1989 Apr    | Uranus, $\eta$ Car | 1 $\times$ 8 | 95 | Fomalhaut | 240 |
| 1990 May    | Ceres, $\eta$ Car | 2 $\times$ 10 | 95 | Fomalhaut | 245 |
| 1991 Apr    | Ceres, $\eta$ Car | 2 $\times$ 10 | 95 | Fomalhaut | 240 |
| 1992 Mar    | Uranus, $\eta$ Car, Calisto, Ceres, Neptun, Ganymede | 2 $\times$ 10 | 47, 95 | $\beta$ Pic | 115 |
| 1993 Apr/May | Uranus, $\eta$ Car | 2 $\times$ 10 | 47, 95 | Fomalhaut | 250 |
|             |            |           | 95 | HD 135344 | 95 |
|             |            |           | 95 | HD 139614 | 90 |
| 1994 Jul/Aug | Uranus, $\eta$ Car | 2 $\times$ 10 | 47, 95 | Fomalhaut | 245 |
|             |            |           | 95 | HD 135344 | 105 |
|             |            |           | 95 | HD 142527 | 90 |
|             |            |           | 95 | HD 169142 | 125 |

### 3. OBSERVATIONAL RESULTS

The results for all the objects observed are shown in Figures 1, 2, 3, and 4 and in Table 2. The figures illustrate the spatial results and relevance of our flux density measurements to the overall energy distributions, and the table lists peak flux densities in our KAO beams relative to the *IRAS* large-beam results. Several of the figures also include modeling results that will be discussed below.

For $\beta$ Pic it was impossible to schedule flights at a time when the orientation of our array would be along the major axis of the circumstellar disk. Therefore, our observations consist of peak flux measurements with the central pixel of the array (Table 2), together with measurements of several points $1/2$ and 1 beamwidth on either side of the star along a line through the optical circumstellar disk (Fig. 1, where all measurements on either side have been averaged to improve the signal-to-noise ratio). The peak flux data (Table 2) show that at 95 $\mu$m the circumstellar cloud is marginally resolved in our KAO beam relative to the *IRAS* beam; at 47 $\mu$m there is clear evidence with our much smaller KAO beam that the cloud is resolved in the peak flux data; the 47 $\mu$m spatial data are also consistent with the idea that the source has been resolved, although they are certainly not compelling.

Our Fomalhaut data are summarized in Figure 3 and Table 2. The 1988 data are the only observations made with the long axis of our array essentially parallel to the *IRAS* in-scan direction, along which the source appeared to be resolved by *IRAS*. All of the other 95 $\mu$m observations, as well as the only 47 $\mu$m observations, were made with the array roughly parallel to the *IRAS* cross-scan direction, along which Fomalhaut showed no evidence for resolution by *IRAS*. As noted in a preliminary report on our first

![Fig. 1.—Observational and model results for model B10A for $\beta$ Pic. Dotted line: model spatial profile at infinite spatial resolution; dashed line: our KAO point-source profile (PSP); solid line: model convolved with PSP; open triangles: observed average source brightness $1/2$ and 1 beamwidth off center relative to the peak observed flux at 47 $\mu$m. The error bars indicate the combined statistical and calibration uncertainties.](image)

### TABLE 2

| Star        | KAO $F_\lambda$ (Jy) | Uncertainty (statistical, total) | $\lambda$ (\(\mu\)m) | *IRAS* $F_\lambda$ (Jy) | $\lambda$ (\(\mu\)m) |
|-------------|----------------------|---------------------------------|-----------------------|--------------------------|-----------------------|
| $\beta$ Pic | 12.9                  | $\pm 1.0, \pm 1.6$              | 47                    | 18.8 $\pm 0.9$           | 60                    |
|            | 8.5                   | $\pm 0.6, \pm 1.0$              | 95                    | 11.2 $\pm 1.0$           | 100                   |
| Fomalhaut  | 5.6                   | $\pm 0.65, \pm 0.95$            | 47                    | 9.8 $\pm 0.5$            | 60                    |
|            | 6.7                   | $\pm 0.6, \pm 1.0$              | 95                    | 11.3 $\pm 1.1$           | 100                   |
| HD 135344  | 24.3                  | $\pm 1.8, \pm 3.5$              | 47                    | 26.3 $\pm 1.5$           | 60                    |
| HD 139614  | 14.0                  | $\pm 1.3, \pm 2.5$              | 47                    | 18.3 $\pm 1.2$           | 60                    |
| HD 142527  | 98                    | $\pm 2.0, \pm 15$               | 47                    | 106 $\pm 6$              | 60                    |
|            | 84                    | $\pm 1.2, \pm 12$               | 95                    | 82 $\pm 5$               | 100                   |
| HD 169142  | 22.9                  | $\pm 2.1, \pm 3.5$              | 47                    | 28.9 $\pm 2$             | 60                    |
observations by Lester et al. (1990), our spatial data along the IRAS in-scan direction appear to resolve the circumstellar cloud at 95 μm. In the perpendicular direction (all our other data), there is some evidence for resolution at 47 μm, and slight evidence at 95 μm. In the comparison of the peak flux measured in the KAO beam relative to the IRAS beams, however, Table 2 shows strong evidence that Fomalhaut is resolved in all the KAO observations, assuming there has not been significant far-infrared variability over this timescale.

For the Walker & Wolstencroft (1988) objects all of the spatial data (Fig. 4) are completely consistent with their circumstellar clouds being pointlike at the KAO resolution. The flux density results in Table 2, however, show that in two of the four observed cases, the 47 μm KAO flux measurements are lower than the IRAS fluxes by slightly more than the combined 1σ uncertainties in both. We do not consider this strong evidence for resolution of the clouds, but it suggests that there may be a small amount of emitting dust beyond the limits of the KAO beam.

4. MODELING

In order to compare our size information on these stars quantitatively with the IRAS data and to determine the implications of our data for the properties of the circumstellar clouds, we have tried fitting simple models to the available data. These models were designed to be similar to those that Backman, Gillett, & Witteborn (1992, hereafter BGW) constructed for β Pic, and we have extended them to Fomalhaut as well. The basic structure of the models assumes a spatially and optically thin disk. For β Pic the disk was assumed to be edge-on as suggested by the optical imagery; for Fomalhaut the inclination angle was allowed to vary. The circumstellar dust was assumed to be distributed in a single power-law distribution between an inner and an outer radius, or, for the most successful β Pic models, to have an inner distribution with one power law, optical depth, and emissivity law, together with an outer distribution with a different combination of power law, optical depth, and emissivity. In the latter two-component models, the radius dividing the two regions was fixed at the value used by BGW of 80 AU. The emissivity law for the dust in either component was characterized in a simple way; shortward of a specified wavelength, λ₀, the emissivity was assumed to be constant; longward of that wavelength it was assumed to decrease as either $\epsilon \propto \lambda^{-1}$ or $\epsilon \propto \lambda^{-2}$, although no models with a $\lambda^{-2}$ dependence provided good fits to any of the data.

4.1. β Pic

Our aim in modeling β Pic was, first, to reproduce the results of BGW, and then to determine what additional constraints our data placed on their model results. BGW found that they were only able to fit the spectral and spatial data on β Pic with two-component models which had a substantially lower dust density distribution inside a radius of order 100 AU. They confirmed Gillett’s (1986) conclusion that (1) on average the grains around β Pic were smaller than those around Vega and Fomalhaut (i.e., $\lambda_0$ of the order of a few microns) and (2) the inner radius for any thermally emitting dust, though model dependent, was of order 5–20 AU.

The additional constraints which we used from our data were the total flux densities measured in our KAO beams and the spatial data at 47 μm. Also, subsequent to BGW’s paper, Zuckerman & Becklin (1993) published results of submillimeter photometry and mapping of β Pic and Fomalhaut. We have also included their 800 μm data, although small differences in the assumed emissivity law in the far-infrared can make almost any of the realistic models fit the 800 μm photometry.

The two best-fitting models of BGW were those labeled 10 and 11 in their paper. In both, the radius where the density changed from low to high was 80 AU, and the surface density power law was set at $-1.7$ in the outer region to match that inferred from the optical coronagraphy. The major differences in the two models were that model 10 used smaller grains and a larger inner radius to reproduce the shorter wavelength emission, and model 11 allowed a different power law for the density gradient in the inner disk region but assumed identical grain properties in both regions. Because these provided the best fits to the data available to BGW, we attempted to fit our data as well as the previous data with one or both of these two models. Our results are shown in Figures 1 and 2 for a model we have labeled B10A, which is quite similar to model 10 of BGW; we also found a model similar to their model 11 (which we called B11A) that gives comparable results, which are not shown here. Figure 1 shows our spatial data relative to the model prediction; Figure 2 shows the model energy distribution, both total flux density, and flux density in various aperture sizes, including the IRTF 4" and 8" mid-infrared data discussed by BGW, our 47 and 95 μm KAO data, and Zuckerman & Becklin’s (1993) 800 μm obser-
Fig. 3.—Model results for the best-fit model described in the text and Table 4 for Fomalhaut, together with various observations. The spatial scan panels show our observed 47 and 95 $\mu$m data relative to the model results, assuming that our (and the IRAS) data were taken exactly parallel and perpendicular to the disk axis. The KAO point-source profiles are shown as dashed lines. The energy distribution panel shows the model results, both for the total flux and for that contained within the KAO beam at 47 and 95 $\mu$m and the 800 $\mu$m beam of Zuckerman & Becklin (1993) (dotted curve). The IRAS data are also shown close to (except at 12 $\mu$m) the solid, total flux line. The error bars indicate the combined statistical and calibration uncertainties.

Fig. 4.—Our observational spatial data on the four observed stars in the Walker & Wolstencroft (1988) list (points) relative to the point-source profile (dash-dot line). none of these stars shows evidence for spatial resolution in these data. The error bars indicate the combined statistical and calibration uncertainties.
vations. Both models 10A and 11A provide a reasonable fit to all the data. The parameters for these models are listed in Table 3. We also confirmed that single-density-gradient models could not reproduce the observations. Two different regions with densities differing by a factor of 15–20 are required to produce enough far-infrared emission without overproducing the near-infrared emission and to fit the observed spatial extent in the 10–20 μm spectral region.

4.2. Fomalhaut

Gillett (1986) suggested simple models for the circumstellar clouds around the four original Vega-like stars to explain the IRAS photometry and scan data. For Fomalhaut he found that a distribution of black grains with a mild density gradient over a range of radii, 28–140 AU, gave a reasonable fit to the IRAS data. Therefore, we began our attempts to fit the IRAS, KAO, and submillimeter data (Zuckerman & Becklin 1993) with a distribution of grains with λ0 ∼ 100 μm and a similar density gradient and range of radii. The facts that (1) the IRAS in-scan and cross-scan source sizes were clearly different and (2), somewhat “accidentally,” our KAO observations provided one-dimensional source profiles roughly along the same direction as the IRAS data suggested that we model the circumstellar cloud as an inclined disk. With no additional data or constraints on the disk inclination, and without knowing the orientation of the IRAS or KAO scans relative to the disk, we have fitted the data assuming that the IRAS in-scan data and the 1988 KAO data were taken along the long axis of the source and that the IRAS cross-scan and subsequent KAO data were taken along the short apparent dimension. Because of this free parameter and the smaller quantity of spatial observations available than for β Pic, we concentrated our efforts on simple models with one dust density gradient and one type of dust between an inner and outer radius. This implies six free parameters for these models: surface density power law, inner and outer radii, λ0, optical depth, and inclination angle relative to the line of sight. For all the models we assumed a λ−1 emissivity law for λ > λ0.

Figure 3 shows the results of the fits for the best model we found; the details of this model as well as models with other density gradients producing acceptable fits are listed in Table 4. The most important general features of models producing acceptable fits are (1) a large range of radii over which a substantial amount of dust exists, (2) grains which have constant emissivity out to λ ∼ 100 μm, and (3) inclination angles between 45° and 75°. (Because of the unknown orientation of the observations relative to the supposed disk, these values represent lower limits to the disk orientation). Surface density gradients, σ ∝ r−n, with n ∼ 0.5 ± 0.5 provide the only reasonably acceptable fits. Steeper gradients put too much flux into the KAO beam relative to the IRAS beam for models which reproduce the IRAS total fluxes; shallower density gradients have the opposite problem (as well as being difficult to understand on physical grounds). A relatively large range in radii for the dust is needed to explain the decrease in flux observed with the KAO relative to IRAS; the derived range of inclination angles for the model disks is required to fit the differences in flux density observed in different array orientations on the KAO (as well as IRAS) and the spatial KAO data.

4.3. Walker-Wolstencroft Stars

We have not performed any detailed modeling to fit the data on these objects, for the following reason. For all these stars that we observed, simple-minded models of circumstellar dust shells suggest that the shells should not be resolvable at the KAO limit even for dust grains with properties comparable to typical interstellar grains. For example, if we assume a single-temperature dust shell whose temperature is determined by radiative equilibrium between power absorbed with efficiency εa and power radiated with efficiency εr, the calculated diameter of the circumstellar shells for these four stars ranges from 3° for HD 169142 to 10° for HD 142527 for a ratio εa/εr = 100, typical of normal interstellar grains at temperatures of ∼100 K. For blacker grains, the radius of a dust shell in thermal equilibrium would only be smaller than the above sizes, so we have no constraints on dust properties for grains in thermal equilibrium. Clearly, this also implies that if IRAS indeed resolved some of these dust shells, the extended emission must be due to faint, low-level, extended dust that is cooler than the bulk of the dust contributing to the far-infrared fluxes reported by Walker & Wolstencroft (1988) (and con-

| Parameter | Model B10A | Model B11A |
|-----------|------------|------------|
| Inclination angle (deg) | 90 | 90 |
| Inner radius (AU) | 20 | 5 |
| Middle radius (AU) | 80 | 80 |
| Outer radius (AU) | 2000 | 2000 |
| γ (inner) | −1.77 | −0.4 |
| τ (outer) | −1.7 | −1.7 |
| λ0 (inner) (μm) | 0.3 | 2.5 |
| τ100 (inner) | 2.9 × 10−4 | 2.8 × 10−4 |
| τ100 (inner) | 5.1 × 10−3 | 5.0 × 10−3 |
| n | −1 | −1 |

a Surface density ∝ r2.

b Dust emissivity ∝ λ2.

| Parameter | Model 1 | Model 2 | Model 3 |
|-----------|---------|---------|---------|
| Inclination angle (deg) | 60 | 65 | 50 |
| Inner radius (AU) | 22 | 16 | 25 |
| Outer radius (AU) | 430 | 300 | 400 |
| γ | −0.5 | 0 | −0.75 |
| λ0 (μm) | 80 | 80 | 85 |
| τ100 | 2.7 × 10−5 | 6.4 × 10−5 | 5.6 × 10−5 |
| n | −1 | −1 | −1 |

a Surface density ∝ r2.

b Dust emissivity ∝ λ2.
firmed by our KAO photometry). Perhaps a small number of tiny grains that are not in thermal equilibrium could explain the IRAS results.

5. CONCLUSIONS

The basic conclusion from our high-resolution work is that the models that explain the lower resolution IRAS data for β Pic and Fomalhaut are quite consistent with our higher resolution KAO observations. Our most important conclusion for β Pic is that, like BGW, we find that its circumstellar disk can be well fitted with a two-component model whose main features are a substantially lower dust density inside ~100 AU and dust grains with a characteristic size of the order of a few microns. For Fomalhaut our most important conclusions are, first, that we confirm Gillett’s (1986) suggestion that the grains must be essentially black out to the longest wavelengths observed by IRAS and the KAO, 100 μm. Second, the dust density gradient around Fomalhaut is probably in the range \( \rho \propto r^{-0.5 \pm 0.5} \). In addition, we find some evidence that Fomalhaut’s circumstellar disk axis is likely to be inclined substantially to the line of sight, though the data do not seem consistent with an angle as high as that of β Pic. These conclusions show that the disks around β Pic and Fomalhaut are different in a number of important ways. In addition to Fomalhaut’s having substantially lower optical depth (as do all the other related stars), there are large differences in particle size and in density gradient.

Our results on the four stars in Walker & Wolstencroft’s (1988) list are difficult to reconcile with their analysis of the IRAS data, which suggested that these stars have resolved dust shells in the far-infrared at the IRAS resolution of ~1″–2″. With our KAO resolution of 10″–20″, these stars should have been easily resolved. Instead, we found them to be essentially pointlike, both in the spatial cuts and by a simple comparison of KAO and IRAS flux densities. The observed dust temperatures and assumption of grain sizes even as small as typical interstellar grains do not require the dust shells to be large enough to be resolved by the KAO. Therefore, we cannot put any significant limits on the dust properties around these stars. On the other hand, the fact that we have not resolved them, even though they appeared to be in the IRAS data, suggests that a careful search for faint, extended emission by the Infrared Space Observatory would be worthwhile.

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