ISOPHOT Observations of Dust Disks around Main Sequence (Vega-Like) Stars

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Received September 15, 1998; revised June 24, 1999

The photometer (ISOPHOT) on the Infrared Space Observatory (ISO) has proved to be invaluable for investigating the dust around main sequence stars (both prototypes and candidate Vega-like stars). The long wavelength camera (at 60 and 90 μm) has been used to map the area around the stars to establish whether the dust disk is extended. Low-resolution spectra between 5.8 and 11.6 μm show whether dust is composed of silicate grains, and whether molecular features are present. The four prototype Vega-like stars (Vega, β Pic, Fomalhaut, ε Eri) are studied, as well as eight other stars, which are main sequence stars with cool dust. We find that the spectra of β Pic, 49 Cet, HD 98800, and HD 135344 show excess emission from the cool dust around the star, HD 144432 and HD 139614 show silicate dust emission, HD 169142 and HD 34700 show emission features from carbon-rich molecules (possibly PAHs, polycyclic aromatic hydrocarbon molecules), and HD 142666 shows emission features from both carbon-rich molecules and silicate dust. Up to 11.6 μm, the emission from Vega, Fomalhaut, and ε Eri is dominated by the stellar photosphere. At 60 and 90 μm, the extended dust emission is mapped, and the disk resolved in eight cases. The dust mass in the disks is found to range from around 10^{-8} to 10^{-4} M_⊕. Since several of the stars are younger than the Sun, and the disks have sufficient material of the type found in the Solar System, these disks could be in the early stages of planet formation.

Key Words: Vega-like stars; infrared observations; extrasolar planets; planetary formation.

I. INTRODUCTION

Four normal main sequence stars (Vega (α Lyr), β Pic, Fomalhaut (α PsA), and ε Eri), were found by the IRAS satellite to have dust disks around them (Aumann et al. 1984, Gillett 1986). These became the prototype Vega-like stars. The dust disks were cool (around 100 K) and tenuous, with masses of order Moon mass rather than Jupiter mass. The sizes of the disks were deduced to be of order 100 AU, comparable to the size of the clouds of material at the edge of the Solar System. The deductions from the IRAS data were confirmed in the case of β Pic by Smith and Terrile (1984) and others, who imaged the disk in the visible, scattered starlight (at 0.89 μm). Pantin et al. (1997) imaged the disk around β Pic at 12 μm and derived a radial density distribution out to 100 AU. MAuron and Dole (1999) attempted to detect the disk around Vega in polarized light at 0.44 μm. Most recently, the disks of the four prototypes have been imaged at 850 μm (Holland et al. 1998, Greaves et al. 1998), the disk of ε Eri being clearly resolved as a ring about the star. Other stars have been imaged in the near-infrared, namely HD98800 at 4.71 and 9.78 μm, showing there are two components in the near/mid infrared (Gehrz et al. 1999) and HD233517 (SAO26804) at 10 μm (Skinner et al. 1995).

A broad emission feature around 10 μm in the spectrum of β Pic was compared with the emission from Comets (Telesco and Knacke 1991, Knacke et al. 1993). Knacke et al. found that the emission from the dust around β Pic showed structure similar to that from the crystalline silicates found in some comets. Aitken et al. (1993) also found that the 10 μm silicate emission feature was similar to that in Comet Halley. Skinner et al. (1992) found silicate dust emission from HD98800. Sylvester et al. (1996) showed spectra around 10 μm for 13 Vega-like candidates, identifying silicate dust emission and features from carbon-rich molecules (UIRs) in some of them. Walker et al. (1996) and Butner et al. (1997) have also detected silicate emission from several Vega-like candidates around 10 μm. Butner et al. (2000) modeled their spectra using a model based on Comet Hale–Bopp data (which uses pyroxenes and olivines), obtaining good fits to the data for HD142666 and HD35187, but HD144432 required a pyroxene-to-olivine ratio higher than that for the other objects.

The original discovery of the four prototypes prompted several searches of the IRAS data for more main sequence stars with...
cool dust disks, and several lists of candidates have resulted, e.g., Walker and Wolstencroft (1988) (see also the review by Backman and Paresce 1993). The Infrared Space Observatory (ISO) was launched in November 1995 (Kessler et al. 1996) and was operational until April 1998 when the superfluid helium coolant finally ran out. The photometer on board ISO (ISOPHOT) operated between 2.5 and 240 μm, with a variety of detectors, filters, and observing modes (Lemke et al. 1996). Early results have shown the resolved dust disks around Vega (Heinrichsen et al. 1998) and β Pic (Heinrichsen et al. 1999) using high-resolution linear scans at 60 μm. Early maps show that several other disks can be resolved by ISO (Fajardo-Acosta et al. 1997, Walker et al. 1999) at 60 μm. The four prototype Vega-like stars were observed with ISOPHOT to investigate the properties of their dust disks in the infrared. Several candidate Vega-like stars were also observed, and the results for eight targets are given here.

II. OBSERVATIONS

Table I lists the targets observed. The spectral types came from the Bright Star Catalog or from Dunkin et al. (1997). Low-resolution spectra with the long wavelength channel, between 5.8 and 11.6 μm, were taken for all the objects (see Figs. 1 and 2). The long wavelength channel had a linear array of 64 pixels and a resolving power of ~95. The aperture for the spectrometer was 24 × 24 arcsec, and the exposure time for the spectrum was 64 s. Small maps were made at 60 and 90 μm with the small camera on ISOPHOT, using the raster mode of the satellite, and additionally using the chopper in the ISOPHOT instrument to increase the sampling. The raster point step size was 60 arcsec and the line step size was 30 arcsec, with a chopper step of 15 arcsec. The camera had 9 pixels with a pixel size of 43.5 × 43.5 arcsec. HD144432 was not observed in the mapping mode, and the observation of HD142666 failed toward the end of the first map, at 60 μm, so no data were obtained at 90 μm. A high-resolution linear scan at 60 μm was made across the disk for four stars. The step size was 6 arcsec, which was matched to the point spread function and exploited the excellent pointing accuracy of the ISO satellite (see Heinrichsen et al. 1998 for more information). Calibration maps were made of γ Dra (HR6705), a star with no circumstellar material, to be used as a point source reference. Two scans were made for Vega, with a separation of around 325 days. The results from the two scans were identical, showing that the instrument remained stable during the mission. The two scans of Vega are shown in Fig. 3, the small offset in pointing on the first scan across Vega is not corrected, to show clearly the accuracy of the ISO pointing. HD142666 and HD169142 were observed once using the high-resolution scan mode. For β Pic, the disk was mapped using several high-resolution scans, at 25 and 60 μm (Heinrichsen et al. 1999).

The noise in the observation depends partly on the position in the ISO orbit, since the data taken soon after curing of the detectors (which happened twice per orbit) were less noisy and the responsivity of the detector could be more accurately determined. Observations taken near the beginning or end of the scientific window of the orbit had higher noise due to the Earth’s radiation belts. The data were reduced from the raw data stage (ERD) using the ISOPHOT Interactive Analysis package, PIA 7.3, (Gabriel et al. 1997), which included a post-mission calibration update.

For the spectra, the dynamic spectral response correction (Klaas et al. 1997) was used, where each of the 64 pixels was calibrated using two calibration stars with similar fluxes at that

<table>
<thead>
<tr>
<th>Star</th>
<th>Sp. type</th>
<th>Spectrum</th>
<th>Map size (60/90°)</th>
<th>Angle (Z axis) (°)</th>
<th>Scan (60°)</th>
<th>Angle (°)</th>
<th>T_{bb} (°K)</th>
<th>T (°K)</th>
<th>Emissivity (λ)</th>
<th>Flux at 200 μm (Jy)</th>
<th>Dust mass (M_{⊙})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vega</td>
<td>A0V</td>
<td>Photosphere</td>
<td>24/36</td>
<td>112.2</td>
<td>19</td>
<td>103</td>
<td>95</td>
<td>65</td>
<td>−1.0</td>
<td>1.58 × 10^{−9}</td>
<td>4.0 × 10^{−9}</td>
</tr>
<tr>
<td>β Pic</td>
<td>A5V</td>
<td>Cool thermal</td>
<td>26/28</td>
<td>43.1</td>
<td>12.4</td>
<td>30</td>
<td>105</td>
<td>65</td>
<td>−1.0</td>
<td>2.06 × 10^{−8}</td>
<td>3.2 × 10^{−8}</td>
</tr>
<tr>
<td>Fomalhaut</td>
<td>A3V</td>
<td>Photosphere</td>
<td>19/30</td>
<td>59.0</td>
<td></td>
<td></td>
<td>80</td>
<td>55</td>
<td>−1.0</td>
<td>2.82 × 10^{−9}</td>
<td>8.4 × 10^{−9}</td>
</tr>
<tr>
<td>ε Eri</td>
<td>K2V</td>
<td>Photosphere</td>
<td></td>
<td>71.8</td>
<td></td>
<td></td>
<td>90</td>
<td>50</td>
<td>−1.0</td>
<td>1.88 × 10^{−9}</td>
<td>1.1 × 10^{−9}</td>
</tr>
<tr>
<td>49 Cet</td>
<td>A3V</td>
<td>Cool thermal</td>
<td></td>
<td>75.2</td>
<td></td>
<td></td>
<td>80</td>
<td>60</td>
<td>−1.0</td>
<td>0.32 × 10^{−8}</td>
<td>5.5 × 10^{−8}</td>
</tr>
<tr>
<td>HD98800</td>
<td>K5Ve</td>
<td>Cool thermal</td>
<td></td>
<td>125.1</td>
<td></td>
<td></td>
<td>165</td>
<td>45</td>
<td>−2.0</td>
<td>0.63 × 10^{−8}</td>
<td>6.7 × 10^{−8}</td>
</tr>
<tr>
<td>HD139614</td>
<td>A7Ve</td>
<td>Silicate</td>
<td></td>
<td>109.6</td>
<td></td>
<td></td>
<td>135</td>
<td>45</td>
<td>−1.5</td>
<td>3.92 × 10^{−6}</td>
<td>4.5 × 10^{−6}</td>
</tr>
<tr>
<td>HD135344</td>
<td>F4Ve</td>
<td>Silicate</td>
<td>21/10</td>
<td>107.4</td>
<td></td>
<td></td>
<td>85</td>
<td>50</td>
<td>−1.1</td>
<td>9.53 × 10^{−5}</td>
<td>8.1 × 10^{−5}</td>
</tr>
<tr>
<td>HD144432</td>
<td>A9/F0Ve</td>
<td>Silicate</td>
<td>xxxxx</td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td>50</td>
<td>−2.0</td>
<td>1.59 × 10^{−5}</td>
<td>4.5 × 10^{−6}</td>
</tr>
<tr>
<td>HD169142</td>
<td>A5Ve</td>
<td>C-rich</td>
<td>−/−54</td>
<td>84.7</td>
<td>(4.0)</td>
<td>90</td>
<td>115</td>
<td>55</td>
<td>−1.0</td>
<td>6.54 × 10^{−5}</td>
<td>4.3 × 10^{−5}</td>
</tr>
<tr>
<td>HD34700</td>
<td>G0V</td>
<td>C-rich</td>
<td>12/−</td>
<td>58.3</td>
<td></td>
<td></td>
<td>100</td>
<td>60</td>
<td>−1.1</td>
<td>2.19 × 10^{−7}</td>
<td>5.7 × 10^{−7}</td>
</tr>
<tr>
<td>HD142666</td>
<td>A8Ve</td>
<td>Silicate + C-rich</td>
<td>27/xx</td>
<td>101.6</td>
<td>7.8</td>
<td>102</td>
<td>175</td>
<td>110</td>
<td>0.0</td>
<td>2.58 × 10^{−6}</td>
<td>6.7 × 10^{−6}</td>
</tr>
</tbody>
</table>

Note: The map size (the deconvolved full-width-half-maximum) is measured in the Z direction on the 60- and 90-μm maps. 49 Cet is not resolved at 60 μm. The angle is the position angle of the Z axis relative to North in the equatorial coordinate system. The scan (size) is the deconvolved Gaussian width at 60 μm from the high-resolution scan, where available. HD169142 is not resolved. The dust blackbody temperature and emissivity law are given, where they have been calculated from the ISOPHOT photometry between 60 and 240 μm. The blackbody temperature from Walker and Wolstencroft (1988) using IRAS data from 12 to 100 μm is given for comparison.
ISOPHOT OF OBSERVATION OF VEGA-LIKE STARS

FIG. 1. Low-resolution spectra of Vega-like stars: the first column contains Vega, Fomalhaut, and $\epsilon$ Eri, and the second column contains $\beta$ Pic, 49 Cet, and HD98800. The x-axis is in micrometers, the y-axis in watts per squared meter per micrometer.

wavelength. Vega was excluded from the calibration data set when the observed spectrum of Vega was processed. All stars with spectral types later than K1 were excluded from the calibration due to concern about a feature from SiO in their photospheres not included in the models. This meant that some pixels in some spectra had no close match to the observed flux, increasing the possible error in calibration (reflected as large error bars in Figs. 1 and 2). The absolute flux calibration is now better than 20%. The spectra of Fomalhaut and HD139614 were corrected for pointing errors, which were sufficiently large (±2.2
and $-2.5$ arcsec in spacecraft $Y$ direction respectively) to affect the responsivity used.

For the maps and scans the internal calibration source (Schulz et al. 1999) was used to give the actual responsivity for that observation. However for the maps of HD169142, where the calibration source saturated the detector, and for the map of HD142666, where the observation failed before the second calibration observation, the orbital dependent default responsivity was used. For the maps, a calibration observation was taken at the start and at the end of the map in each filter, and the responsivity interpolated through the raster map. The data were deglitched at the second stage of processing and the first half of the data in
each chopper plateau was discarded to reduce the detector drift errors. The uncertainty in absolute flux level at 60 and 90 μm is 20%. For the photometry from 60 to 200 μm (at seven wavelengths—60, 80, 100, 120, 150, 170, and 200 μm) used to estimate the dust temperatures and emissivities, the uncertainty in absolute flux level is between 10 and 20%, dependent on the filter (see Klaas et al. 1998).

III. RESULTS

The spectra are shown in Fig. 1 and Fig. 2. The flux is given in watts per squared meter per micrometer and the uncertainty in the absolute flux level is 20%. The error bars shown in the figures are the formal uncertainty in the measurement, and do not include instrumental effects such as detector drift or pointing error, but do include the error from the dynamic spectral response correction. The spectra mainly confirm earlier work, but they do not have the large uncertainties around 9.7 μm due to the ozone correction from ground-based work, and they extend the spectra to 5.8 μm. For some objects (Vega, Fomalhaut, ε Eri) the stellar photosphere dominates the spectrum to 11.6 μm. The other spectra show either the cool thermal excess, the broad feature around 10 μm due to silicate dust emission, or the sharper molecular features due to carbon-rich molecules, often called UIRs (unidentified infrared features) or PAHs (polycyclic aromatic hydrocarbon molecules). The 6.2- and 7.7-μm features arise from C–C bonds, the 8.6- and 11.3-μm features from C–H bonds.

The spectrum of β Pic shows excess emission from 8 μm onward, due to the thermal emission from the cool dust shell. The silicate emission feature is also present (see Butner et al. 2000), but the feature does not dominate this spectrum. The situation is similar for HD98800; however Sylvester et al. (1996) with their coverage to longer wavelengths show that HD98800 (SAO179815) has a very broad silicate dust emission feature. HD135344 and 49 Cet also show excess emission at the longer (spectral) wavelengths due to cool dust. HD169142 (Sylvester et al. show the 11.3-μm feature) and HD34700 show emission features at 6.2 and 7.7–8.6 μm from the C–C and C–H bonds, often attributed to PAHs. The 11.3-μm feature is not strong, but it occurs where the instrument sensitivity is lower. HD139614 may show a feature around 6.2 μm. The silicate feature for HD144432 is relatively sharp (see also Sylvester et al.), similar to that found from the dust around some young T Tau stars, such as GW Ori (Cohen and Witteborn 1985). HD142666 shows features from both silicate dust and carbon-rich molecules (particularly the 6.2- and the 11.3-μm features), the spectrum shown by Sylvester et al. (1996) may also show the 11.3-μm feature, noted by them as a point of inflection. The silicate dust can be attributed to olivines and pyroxenes, which may be similar to material found in primitive Solar System material (see Butner et al. 2000). Some comets, for example Comet Halley and Comet Bradfield 1987 XXIX, show the crystalline silicate feature at 11.2 μm, attributed to small olivine particles (Hanner et al. 1994).

The maps were orientated with respect to the spacecraft Z axis (see Fig. 4). The position angle of this axis in the astronomical equatorial coordinate reference frame (RA-Dec) is given in Table I. The width of the extended emission (in arcsec) at 60 and 90 μm around the star is only measured in the Z direction, because the detector response significantly affected the measurements along the scan lines in the Y direction (e.g., the “ghost” caused by the chopping can be seen in some of the maps in Fig. 4), and these effects have not been completely eliminated yet. For ease of comparison with other work, the sizes of the disks are expressed in terms of deconvolved full-width-half-maximum (FWHM) values in arcseconds; the FWHM is measured at 50% peak intensity, whereas the Gaussian width is measured at 60% of peak intensity. The width measured from the map is deconvolved using a width measured from a similar map of α Boo at 60 μm and γ Dra at 100 μm (scaled to 90 μm using the ISOPHOT Observer’s manual) representing a point source, assuming the point spread function is Gaussian. The mapping mode of ISOPHOT is not scientifically validated due to the uncertainties in the detector drifts and the uncertainties in the value of the point spread function, so the numbers here must be treated with extreme caution (for example, the difference in values for HD142666 between the scan and the map).

The deconvolved Gaussian widths for the high-resolution scans, shown only for the 60-μm data, are given in Table I. The high-resolution linear scans made of β Pic and its accompanying comparison, γ Dra, showed the measurements are very close to the Gaussian function assumed (see Fig. 2 in Heinrichsen et al. 1999). The error in the measurement of the Gaussian width are estimated to be ±2 arcsec. Although the observation of HD169142 gives a profile which is broader than the profile of γ Dra, the errors in the flux determination preclude any firm statement that the disk is resolved. Moriarty-Schieven et al. (2000) resolved the disk at 450 and 850 μm, and their results...
showed that ISO did not scan the disk at the "best" angle. The disk around HD142666 is just resolved, and this represents the limit this technique could achieve. However, Moriarty-Schieven et al. (2000) did not resolve the disc at 450 or 850 μm, although the temperature derived for the dust (see Table I) is higher than that for the other targets.

A second high-resolution scan on Vega (Fig. 3) confirmed the results published earlier (Heinrichsen et al. 1998), showing the
stability and reproducibility of the method. As the second scan was obtained at a different angle through the disk, it confirms that
the Vega disk is symmetrical at the resolution obtainable with
this method, although the scans did not cross the peak observed
by Holland et al. (1998) at 850 μm.

IV. DISCUSSION

Photometry at seven wavelengths between 60 and 240 μm was taken, and the derived temperatures and emissivity laws are shown in Table I. The temperatures for Vega and β Pic, derived using this simple fit, are slightly different from the previously published values of 73 K with \( \lambda^{-1.1} \) for Vega (Heinrichsen et al. 1998) and 85 K with \( \lambda^{-1} \) for β Pic (Heinrichsen et al. 1999), and hence reveal the uncertainties in this simple determination. The temperatures calculated here (see Table I) are lower than the blackbody temperatures derived by Walker and Wolstencroft (1988), which were calculated from up to four data points between 12 and 100 μm, showing that the longer wavelength coverage of ISO and the larger number of data points enabled the dust emissivity and the dust temperature to be determined.

The dust temperature, the dust temperatures, emissivities, and 200-μm fluxes are used to estimate the dust mass (distances for the stars are given in Walker et al. (1999)), using the equation in Becklin and Zuckerman (1990). The values derived are in the range of \( 10^{-9} \) to \( 10^{-4} \) M\(_{\odot} \), from less than the mass of the Moon to less than the mass of Jupiter.

The disk diameters for the four prototypes have been measured more precisely by Holland et al. (1998) and Greaves et al. (1998) at 850 μm (with a 15-m telescope as opposed to the 60-cm telescope in ISO), and they are able to measure the diameter of the inner edge of the dust disk. They get sizes of 24 × 21 arcsec for Vega, 22 × 11 arcsec for β Pic, 41 × 18 arcsec for α PsA, and a peak ring width of 36 arcsec for ε Eri. The disks around Vega and β Pic have a characteristic diameter around 140 AU, calculated from the Gaussian widths of the high-resolution scans. HD142666 is much further away than Vega and β Pic, with a distance of possibly almost 300 pc (Walker and Wolstencroft 1988), which means that the diameter of the dust disk must be around 1000 AU, comparable to disks around young stars. (HD142666 is not in the Hipparcos catalogue, but the parallax uncertainties of stars in the area suggest a lower limit to the distance of around 300 pc.) The sizes (in arcseconds) from the maps, at this stage of our understanding of the ISOPHOT detector behavior, should be taken more as an indicator as to whether the disk is “resolved” or “not resolved” depending on whether the width is significantly larger than the value used for the point spread function (58.7 arcsec at 60 μm, from α Boo, and 64.8 arcsec at 90 μm from the scaled γ Dra observation at 100 μm). The disks around ε Eri, 49 Cet, and HD139614 are not resolved at either wavelength. The ring around ε Eri is face-on and ISO is more sensitive to warm dust, so the dust observed with ISO may well be from regions inside the ring detected at 850 μm, and hence not resolved. The Vega-like candidates studied here are probably younger than the Sun, since they have residual emission features in their absorption lines (Dunkin et al. 1997), and the disks contain more material than Vega and β Pic (allowing them to be studied at their greater distances), so these stars may represent a precursor phase when material is starting to form into larger bodies, and planet formation will soon commence.

ACKNOWLEDGMENTS

This paper has been based on observations with ISO, an ESA mission with instruments funded by ESA member states (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA. The data in this paper were reduced with PIA, a joint development by the ESA Astrophysics Division and the ISOPHOT Consortium led by the Max Planck Institute for Astronomy (MPIA). Our thanks go to colleagues at MPIA (U. Klaas, P. Abraham, M. Haas) and Rutherford Appleton Laboratory (RAL) (P. Richards and H. Morris) for their help with the data reduction.

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