ISOPHOT observations of dust disks around main sequence (Vega-like) stars

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Abstract

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 60μm and 90μm) has been used to map the area around the stars, to establish whether the dust disk is extended. The low resolution spectrometer, working between 5.8 and 11.6 μm shows whether the dust is composed of silicate grains, and/or whether PAHs (polycyclic aromatic hydrocarbon molecules) are present. The four prototype Vega-like stars are studied, and eight other stars, which are main sequence stars with cool dust associated with them. We find that β Pic, HD98800, HD139614, HD135344, HD144432 show silicate dust emission, HD169142 and HD34700 show emission from PAHs, and HD142666 shows emission features from both PAHs and silicate dust. Up to 11.6μm, the emission from Vega, Fomalhaut, ϵ Eri, and 49 Cet is dominated by the stellar photosphere. At 60μm and 90μm the extended dust emission is mapped, and the disk resolved in several cases. For one star, HD169142, a high resolution linear scan resolves the disk at 60μm, suggesting the disk could be 1000AU across, similar to the type of disk found around young stars. 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.

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 (Gillett, 1986). These became the prototype Vega-like stars. The dust disks were cool (around 100K) and tenuous, with masses of order Moon mass rather than Jupiter mass. The sizes of the disks were deduced to be of order 100AU, 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. Most recently, the disks of the four prototypes have been imaged in the submillimeter (Holland et al, 1998; Greaves et al, 1998). 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 2.5μm and 240μm, with a variety of detectors, filters and observing modes (Lemke et al, 1996). 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 from eight targets are given here.

II. OBSERVATIONS

Table 1 lists the targets observed. The spectral types came from the Bright Star Catalog or from Dunkin et al (1997). Low resolution spectra between 5.8μm and 11.6μm were taken for all the objects. Small maps were made at 60μm and 90μm, using the raster mode of the satellite, and additionally using the chopper in the ISOPHOT instrument to increase the sampling. No data were taken for HD144432, and the observation of HD142666 failed towards the end of the first map, at 60μm, so no data were obtained at 90μm. A high resolution linear scan at 60μm was also 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. Calibration scans 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. 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 25μm and 60μm (Heinrichsen et al, 1998b). The data were reduced from the raw data stage (ERD) using the ISOPHOT Interactive Analysis package, PIA 7.2, (Gabriel et al, 1997), which included calibration updates from close to the end of ISO operations. For the spectra, the orbit dependent default calibration was used, but for the maps and scans the internal calibration source was used to give the actual detector responsivity for that map.

III. RESULTS

The spectra are shown in Fig. 1 and Fig. 2. The flux is given in w m^{-2} μm^{-1}, and the uncertainty in the flux is 30%. For some objects (Vega, Fomalhaut, ϵ Eri, 49 Cet) the stellar photosphere dominates the spectrum to 11.6μm. The other spectra show either the broad feature around 10μm due to silicate dust emission, or the sharper molecular features due to PAHs (polycyclic aromatic hydrocarbon molecules), at 6.2μm, 7.7 – 8.6 μm and 11.3μm. The silicate feature for HD144432 is relatively sharp, similar to that found from the dust around some young T Tau stars. HD142666 shows features from both silicate dust and PAH molecules. The silicate dust can be attributed to olivines and pyroxenes, which may be similar to material found in primitive solar system material. Some comets, for example comet Halley and comet Bradfield 1987 XXIX, show the crystalline silicate feature at 11.2μm, attributed to small olivine particles (Hanner et al, 1994).

The maps were orientated with respect to the spacecraft z-axis (see Fig. 3). The position angle of this axis in the astronomical equatorial coordinate reference frame (RA-Dec) is given in Table 1. The width of the extended emission (in arcsec) at 60μm and 90μm around the star is only measured in the z-direction, because the detector response 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. 3), and these effects have not been completely eliminated yet. The sizes of the disks are expressed in terms of deconvolved Gaussian widths in arcsec; the Gaussian width is measured at 60% of full intensity. The width measured from the map is deconvolved using a width measured from an identical map on a star representing a point source (α Boo), assuming the point spread function is Gaussian. The deconvolved Gaussian widths for the high resolution scans, shown only for the 60μm data, are given in Table 1. 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 (Heinrichsen et al, 1998b). The error in the measurement of the Gaussian width are estimated to be $\pm$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. The disk around HD142666 is just resolved, and this represents the limit this technique could achieve. A second high resolution scan on Vega confirms the result published earlier (Heinrichsen et al, 1998a), 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.

IV. DISCUSSION

Photometry between 60μm and 240μm were taken, and the derived temperatures and emissivity laws are shown in Table 1, where the data have been analysed. The energy distribution for HD34700 is well represented by a pure blackbody of 103K. The temperatures derived for Vega, β Pic, and Fomalhaut show they are surrounded by cool dust, some distance from the star. The disks around Vega and β Pic have a characteristic diameter around 140AU, calculated from the Gaussian widths of the high resolution scans. The disk diameters have been measured more precisely by Holland et al (1998) using the submillimeter with a 15 metre telescope (as opposed to the 60cm telescope in ISO), and they are able to measure the diameter of the inner edge of the dust disk. 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 1000AU, comparable to disks around young stars. The Vega-like candidates studied here are probably younger than the Sun, since they have residual emission features in their absorption lines, and the disks contain more material (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.

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TABLES

Table 1. Spectrum characteristics and map sizes for targets observed

Star	Sp.type	spectrum	map size 60/90 (″)	angle (z-axis) (°)	scan (60) (″)	angle (°)	T (°K)	emissivity λ^n
Vega	A0V	photosphere	22/36	112.2	19	103	73	-1.1
β Pic	A5V	silicate		43.1	12.4	30	85	-1
Fomalhaut	A3V	photosphere	27/37	59.0			57	-1
ϵ Eri	K2V	photosphere	-/27	71.8				
49 Cet	A3V	photosphere		75.2				
HD98800	K5Ve	silicate	-/-	125.1				
HD139614	A7Ve	silicate	-/-	109.6				
HD135344	F4Ve	silicate		107.4				
HD144432	A9/F0Ve	silicate	xxxxx					
HD169142	A5Ve	PAH		84.7	(4.0)	90		
HD34700	G0V	PAH		58.3			103	0
HD142666	A8Ve	silicate+PAH	/xx	101.6	7.8	102		

The map size (the deconvolved Gaussian width) is measured in the z-direction on the 60μm and 90μm maps.

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 60μm 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 60μm and 240μm.

FIGURE CAPTIONS

Figure 1. Low resolution spectra of Vega-like stars; first column contains Vega, Fomalhaut, ϵ Eri, and second column contains β Pic, 49 Cet, HD98800. The x axis is in microns, the y axis in w m^{-2} μm^{-1}.

Figure 2. Low resolution spectra of Vega-like stars; first column contains HD139614, HD135344, HD144432, and second column contains HD169142, HD34700, HD142666. The x axis is in microns, the y axis in w m^{-2} μm^{-1}.

Figure 3. Maps at 60μm (left side) and 90μm (right side) of four stars; HD98800 (top), HD34700, HD169142, and Fomalhaut (bottom). The flux densities are in MJy sr^{-1}, and the maps are displayed in the spacecraft mapping orientation, with the RA-Dec grid overlaid. A 'ghost' caused by the chopper throw can be seen on the right side of several maps.

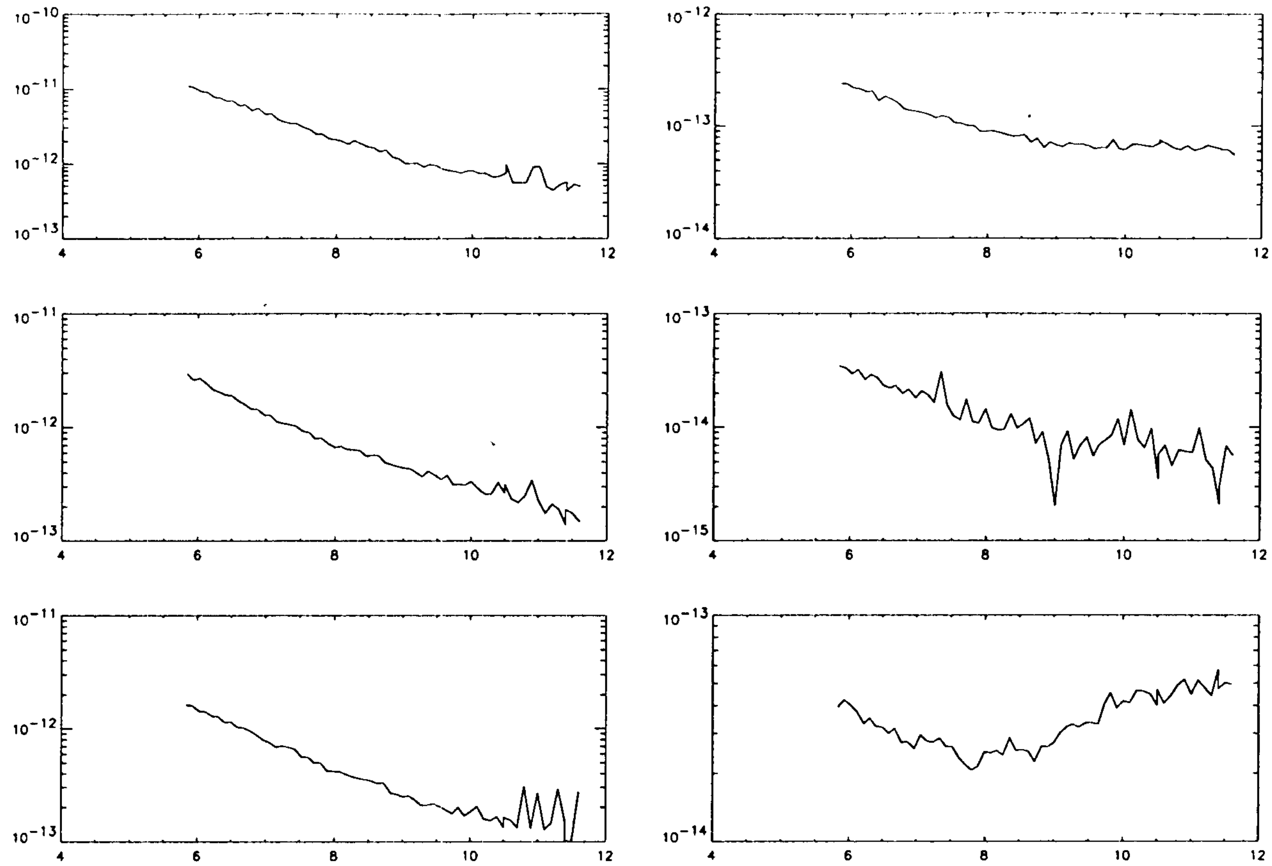

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Figure 1.

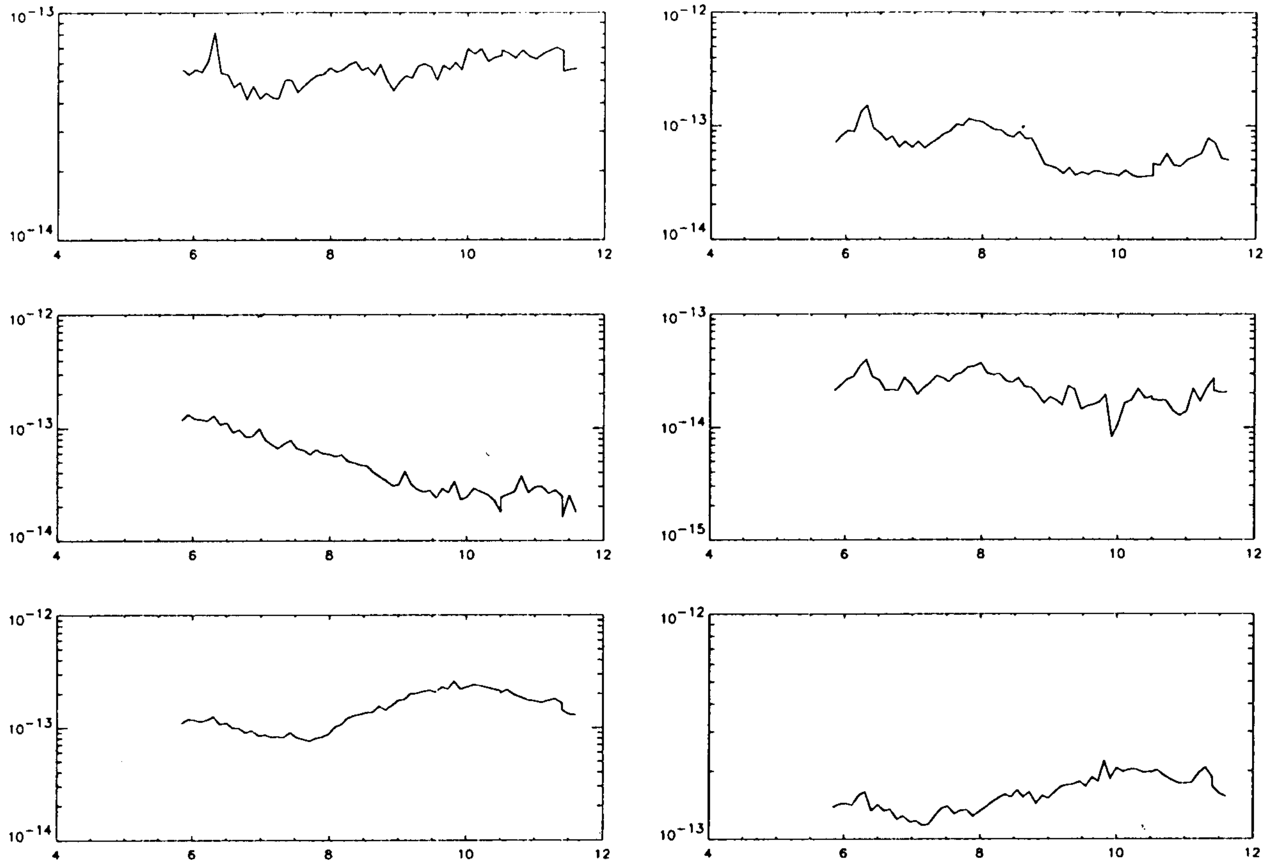

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Figure 2