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Letter to the Editor

IRAS observations of a large circumstellar dust shell around W Hydrae

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Abstract

IRAS observations at 60 and 100 μm reveal a large $30' - 40'$ ($\sim$ 1 pc) diameter dust shell centered on the oxygen-rich red giant W Hydrae. Except for supernovae remnants, this is the largest mass loss envelope, in apparent diameter, known around any evolved star, including planetary nebulae. W Hya's radiation field, stronger than the interstellar radiation field in the outer envelope, is sufficient to heat dust grains with infrared emissivity $\propto \lambda^{-1.2}$ to temperatures $\sim$40 K implied by the ratio of intensities at 60 and 100 μm. A mass loss rate in dust of $4.7 \times 10^{-9} M_{\odot} yr^{-1}$ and total dust shell mass of $\sim$ 1×10^{-4} $M_{\odot}$ are derived from the 100 μm observations. The proximity of W Hya to the Earth ($\sim$100-130 pcs) results in a slow decline of temperature with angular offset from the star. This, in combination with low densities (≤ 0.1 cm^{-3}) in the surrounding interstellar medium, can explain the appearance of a large envelope around a star with a relatively small mass loss rate.

KEY WORDS: infrared radiation - dust - circumstellar matter - mass loss

1. Introduction

The Infrared Astronomical Satellite (IRAS, Neugebauer *et al.*, 1984) has proved to be a useful tool for study of infrared emission from cool dust grains that form in the expanding circumstellar envelopes (CSEs) around red giant stars. Extended 60 and 100 μm emission may indicate the true mass and diameter of CSEs better than molecular emission, which is limited by photodissociation. The large IRAS detectors are ideally-suited to detect low surface brightness objects in non-confused regions far from the galactic plane.

Earlier examination of the IRAS database by Hacking *et al.* (1985) and Gillett *et al.* (1986) revealed a carbon-rich supergiant, R CrB, with a very large 18 arc minute (8 pc) diameter CSE radiating at 60 and 100 μm. As Gillett *et al.* reported, this shell is 20 times larger in linear extent than the largest known CO envelope around IRC +10216 (Knapp *et al.*, 1982) and about 100 times the diameter of the largest known OH/IR maser envelopes (Bowers, 1985) and typical planetary nebulae.

This letter reports the discovery of another evolved star surrounded by a large CSE; W Hya, which displays emission $\geq 6\ \sigma$ above the noise over a region with a diameter $\sim$ 35 arc minutes which is extended well beyond the IRAS in-scan and cross-scan detector sizes of $1.5' \times 4.5'$ and $3' \times 4.5'$ at 60 and 100 μm. W Hya (oxygen-rich, M7-9e, D=95-135 pc, see references in Rowan-Robinson and Harris, 1982 and Cahn and Elitzur, 1979) is one of the nearest red giant stars. We will assume D=130 pc throughout this letter. Additionally, at galactic latitude $b = 33°$, W Hya is removed from the strong infrared background of the galactic plane, and occupies an area of low infrared cirrus emission that might otherwise confuse its surrounding extended emission.

2. Observations

Figure 1 presents the IRAS survey coadd observations of W Hya at 100 μm. W Hya is unresolved at 12 and 25 μm by IRAS, with $45'' \times 4.5'$ beamsize. Unfortunately, W Hya was not observed with the pointed observation mode of IRAS.

The extended emission is attributed to W Hya's mass loss because: 1) the emission is symmetrical and centered on W Hya, with similar 60 and 100 μm diameters, 2) within a square degree of W Hya, there are no associations with objects other than W Hya in the catalogs searched and listed in the point source catalog (psc), and 3) the cirrus flags of the psc and $2° \times 2°$ IRAS fields show little or no cirrus contamination in the region of W Hya. Additionally, the faint extended emission is not a detector memory effect from W Hya's strong point source flux densities (194 Jy at 60 μm, 71 Jy at 100 μm), as other sources with similar or greater flux densities (eg. IRC +10216: 900 Jy at 100 μm, IRC +10011: 71 Jy at 100 μm) do not show similar extended emission. The emission is extended in both cross-scan and in-scan directions, and, although slightly larger in the in-scan direction, the flux densities on the leading part of the scans are equal to the flux densities on the trailing part, indicating no detector memory effect.

At 60 and 100 μm, the psc flux densities from W Hya contaminate the faint extended emission at $\theta \geq 5'$ from the star, due to the gradual decline of the point source profile with angle. Therefore, the point source flux densities from an inner circumstellar shell have been estimated in the same manner as in Appendix A of Gillett *et al.* (1986). At wavelength λ, the flux density $f(\lambda)$ from circumstellar dust inside a sphere of radius r_{max} is

$$f(\lambda) = \pi a^2 Q_0 \lambda^{-p} n_0 r_0^2 D^{-2} \int_{r_{min}}^{r_{max}} B_\nu(\lambda, T) 4\pi r^{2-\gamma} dr \qquad (1)$$

where the grain number density has been expressed as $n(r) = n_0(r_0/r)^\gamma$. In equation 1, dust grains emit blackbody radiation $B_\nu(\lambda, T)$ modified by grain emissivity $Q(\lambda) = Q_0\lambda^{-p}$. The dust temperature is determined from $T(r) = T_0(r_0/r)^{2/(4+p)}$, which results from the assumptions of optically thin emission and heating of grains by W Hya's continuum energy. The normalization T_0 is calculated as discussed in Appendix B of Sopka *et al.* (1985). The dust temperature is determined only by the observed flux of the object, and does not depend on uncertain distance and luminosity estimates. Fitting the IRAS psc flux densities at 12 and 25 μm yields an inner circumstellar dust envelope with a radius of $\theta = 5''$, corresponding to T_{min} = 250 K.

Table 1 presents the IRAS psc and extended flux densities of W Hya. The photospheric contribution, which is about half the point source fluxes in all IRAS bands, is calculated using the 2.2 μm magnitude of -3.08 and 2200 K blackbody fit to the 1.6 - 10 μm observations of Neugebauer, Sargent and Westphal (1971).

Figure 2 shows the in-scan intensity ratio $I_\nu(60\mu m)/I_\nu(100 \mu m)$ as a function of angle θ from W Hya, where $I_\nu(\lambda)$ = $f(\lambda)$/(IRAS beamsize) in Jy/steradian. The figure shows the ratio directly measured by IRAS, and also with the estimated point source components (2) and (3) from Table 1 subtracted. The figure also shows intensity ratios calculated from models that assume grains of a single radius and grain emissivity indices p=1, p=1.2, and p=1.4. The intensity at angle θ from W Hya is

$$I_\nu(\lambda,\theta) = 2\dot{M}_d\kappa(\lambda)(4\pi v_d)^{-1}$$

$$x \int_{b(\theta)}^{r_{max}} B_\nu(\lambda, T(r))/(r^{\gamma-1}(r^2-b^2)^{0.5})dr \qquad (2),$$

where $b = \theta D$ and r_{max} corresponds to $\theta = 20'$. Grain density n_0 at r_0 is expressed as a mass loss rate $\dot{M}_d$ at r_0 by the relation $n_0 = 3\dot{M}_d(16\pi^2 a^3 \rho_g v_d r_0^\gamma r^{2-\gamma})^{-1}$. The dust expansion velocity v_d = 48 km s^{-1} will be discussed later, grain density ρ_g = 3 gm cm^{-3} is assumed, and grain opacity $\kappa(100\mu m)$ = 60 cm^2 gm^{-1} at 100 μm is adopted as a value intermediate between 250 μm opacities used by Hildebrand (1983) and Sopka *et al.* (1985), after extrapolating the 250 μm opacities to 100 μm using emissivity index p=1.2. The minimum value of b occurs at θ = $5''$, which excludes components 2 and 3 of Table 1. Intensity ratios from equation 2 are then convolved with the IRAS point source profiles to produce the model curves in Figure 2.

The IRAS observations are consistent within the errors with a model where normal-sized dust grains with p = 1.2 are heated by W Hya to ~ 55 K at 3′, and ~ 40 K at 10′. Dust emissivity p = 1.2 is close to p = 1.0 obtained between 2.2 and 100 μms from the 2.2 μm silicate opacity (2500 cm^2 gm^{-1}) advocated by Mezger *et al.* (1982) and the 100 μm value (60 cm^2 gm^{-1}) preferred in this letter. The difference may be caused by higher dust emissivity p = 1.55 between 25 and 60 μm found in IRAS data for oxygen-rich stars by Zuckerman and Dyck (1986b).

Figure 3 shows observed IRAS intensity profiles for W Hya and the evolved star IRC +10011 (a representative point source), with model intensities calculated from equation (2).

3. Discussion

The detection of an extended dust CSE around W Hya is perhaps not surprising as it is a very close red giant star with an assortment of detected molecular species including: CO (J=2-1, Zuckerman and Dyck, 1986a, and J=1-0, Kastner *et al.*, 1989), OH 1665/67 MHz emission (Engels, 1979), and strong SiO maser emission (Clark, Troland and Miller, 1985). The $30' - 40'$ diameter of the 100 μm emission from W Hya implies a CSE diameter of order 1 pc.

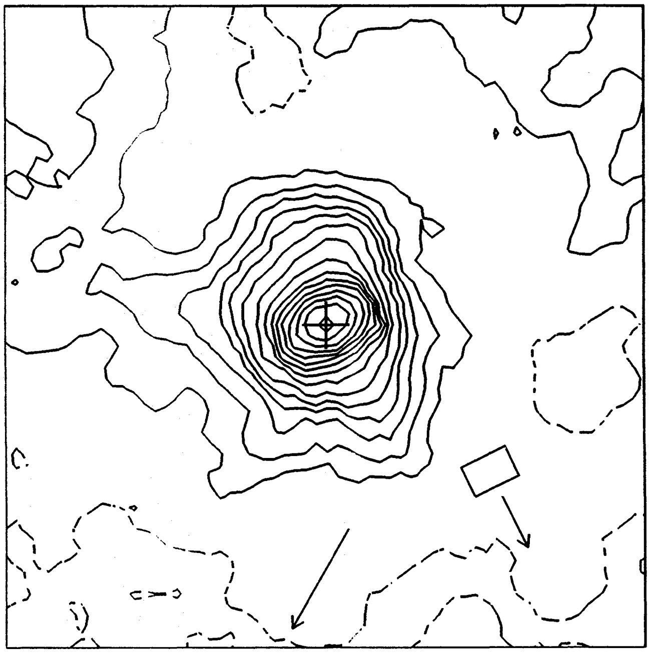

Figure 1. IRAS 100 μm survey coadd intensities of a square region one degree on a side centered on W Hydrae. The cross marks the optical position of W Hya. Solid line contours are 3, 6, 9, 12, 15, 20, 28.3, 40, 56.6, 80, 113.1, 160, 226.3, 320, and 452.5 times the background noise level of 9.96x10^4 Jy/sr. Dashed line contours are -3 and -6 times the noise level. The 100 μm detector size (3′ x 4.5′) is shown to scale, with the short arrow indicating the direction of the IRAS scans. The longer arrow points toward the galactic plane. North is at the top, east to the left

The heating source for dust grains in the outer envelope around W Hya is of interest, since dust temperature as a function of distance from the central star has been measured for very few large CSEs. The interstellar radiation field, which is bluer than that of W Hya, must dominate at some point in the outer envelope. The heating of dust grains in W Hya's outer envelope has been calculated from W Hya's radiation field and the interstellar radiation field in the solar neighborhood (Mathis, Mezger and Panagia, 1983), with dust absorption cross section obtained from the dirty silicate model of Jones and Merril (1976). At 10′ from W Hya, although the interstellar radiation field dominates heating of grains from .09 to .6 μm, heating by W Hya over the total spectrum is $\gtrsim$ 20 times greater.

In contrast to heating of grains by W Hya's radiation field to temperatures that decline gradually with angle from the star, Gillett *et al.'s* (1986) analysis revealed constant $I_\nu(60\mu m)/I_\nu(100\mu m)$=0.3 with angle from R CrB and constant ~ 25 - 30 K dust temperature for the CSE around R CrB. This constant temperature presented a problem, since normal-sized (~ .1μm) grains heated by R CrB's radiation field would reveal a measurable temperature gradient at equilibrium, more steep with angle than that of W Hya. To explain the constant dust temperature, the authors suggested grain heating by an ambient interstellar radiation field $\geq$ 10 times the value in the solar neighborhood, even though R CrB is 1.2 kpc out of the galactic plane.

W Hya's 100 μm non-photospheric point source flux density (~ 30 Jy) yields dust mass loss rates in the range 2 x $10^{-9} \leq \dot{M}_d \leq$ 4.7 x 10^{-9} $M_\odot yr^{-1}$, assuming dust expansion

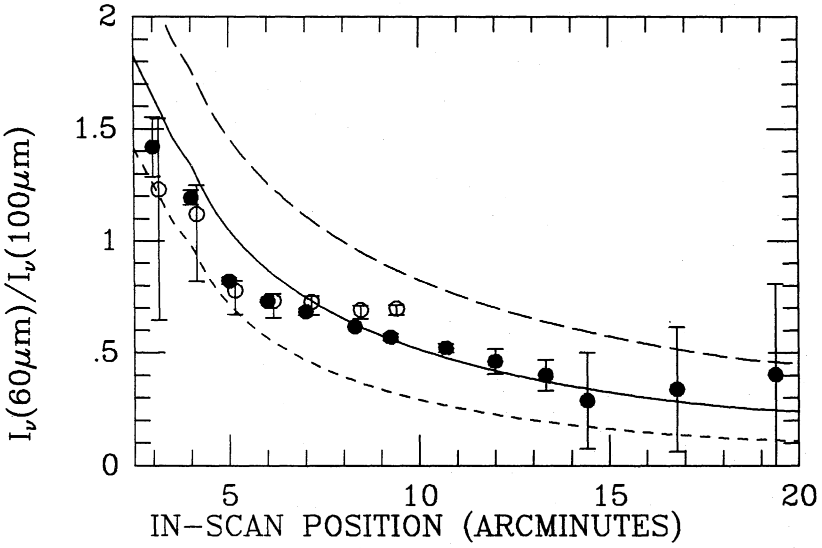

Figure 2. IRAS surface brightness ratio $I_\nu(60\mu m)/I_\nu(100\mu m)$ as a function of angle θ from W Hya. The unprocessed in-scan data is presented as filled dots (•), with error bars representing the difference in the IRAS flux from opposite sides of the star. Open circles (○) represent $I_\nu(60\mu m)/I_\nu(100\mu m)$ after estimated point source profiles $I_\nu(\lambda, \theta)$ (components 2 and 3 of Table 1) are subtracted as discussed in the text. To avoid confusion, the processed profiles (○) are offset by $\theta = .2'$. Error bars result from uncertainties in the 60 and 100 μm point source flux densities. Simulated $I_\nu(60\mu m)/I_\nu(100\mu m)$ profiles are calculated from models of dust heated by W Hya, with density $n(\theta) \propto \theta^{-1}$, and blackbody emission modified by grain emissivity $Q(\lambda) \propto \lambda^{-p}$, with p=1.0, 1.2 and 1.4 (bottom, middle, and top curves respectively)

velocity in the range $21 \leq v_d \leq 48$ km s^{-1}, and 100 μm opacity $\kappa = 60$ cm^2 gm^{-1}. The n(r) $\propto r^{-1}$ density law fit to the observed $I_\nu(100\mu m)$ profile for $3' \leq \theta \leq 15'$ in Figure 3 suggests that W Hya's mass loss rate at 1.2x10^4 years ago (at θ=15', and $v_d = 48$ km s^{-1}) was ~3 times greater than the current mass loss rate.

Mass loss estimates $\dot{M}_{gas} = 5 - 8$ x10^{-8} $M_\odot yr^{-1}$ from CO observations of Wannier and Sahai (1986) and Kastner *et al.* (1989), when compared to $\dot{M}_d$ from the IRAS point source fluxes, yield an abnormally low gas-to-dust ratio of ~ 10-20 for W Hya compared to an average gas-to-dust ratio of ~ 100 for evolved oxygen-rich stars found by Sopka *et al.* (1985). The dust expansion velocity $v_d = v_g + v_{drift}$, which can be substantially larger than the gas velocity v_g for evolved stars with low mass loss rates, can be derived from $v_d = v_g + (L_\star v_g Q_r/\dot{M}_{gas} c)^{1/2}$ (Sopka *et al.*, 1985), where $Q_r = 0.05$ is the average radiation pressure efficiency, and $v_g = 8.8$ km s^{-1} is the CO expansion velocity of Zuckerman and Dyck (1986a). Dust expansion velocities in the range 21-48 km s^{-1} are obtained, using a minimum estimate of $\dot{M}_{gas}$ = 5x10^{-8} $M_\odot$ yr^{-1} from CO line modelling of Wannier and Sahai (1986), and a maximum estimate of $\dot{M}_{gas}$ = 5x10^{-7} $M_\odot$ yr^{-1} from the IRAS point source flux densities, assuming gas-to-dust =200.

The total dust mass of the CSE may be estimated from

$$M_{dtotal} = f_\nu(100\mu m)\, D^2/\, (B_\nu(100\mu m, 40\ K)\, \kappa(100\ \mu m)),$$

which gives 1x10^{-4} $M_\odot$, (with $f_\nu(100\mu m)$ = 100 Jy and $\kappa(100\mu m)$ = 60 cm^2 gm^{-1}), about 100 times less mass than the CSE around R CrB (Gillett *et al.*, 1986).

The Sun and W Hya are inside a local "bubble" in the interstellar medium (ISM)(Cox and Reynolds, 1987) with hotter (T_e = 10^6 K) temperatures and smaller densities (1x10^{-3} $\leq n_{ism} \leq$ .1) than average ISM values. The mass of ISM dust within a 15' radius of W Hya is 4x10^{-8}$\leq M_{ism} \leq$4x10^{-6}$M_\odot$, assuming ISM gas density 1x10^{-3} $\leq n_{ism} \leq$ .1 and dust-to-gas ratio = 1/200. This ISM dust mass is much lower than the 1x10^{-4} $M_\odot$ mass of W Hya's envelope, and therefore, unless ISM densities are $\geq$ 2 cm^{-3} around W Hya, there is insufficient ISM dust to produce W Hya's extended 60 and 100 μm emission.

The observed 15' − 20' radius of W Hya's CSE is smaller than the estimated radius for confinement by pressure from the ISM gas. The distance traveled by a neutral grain before

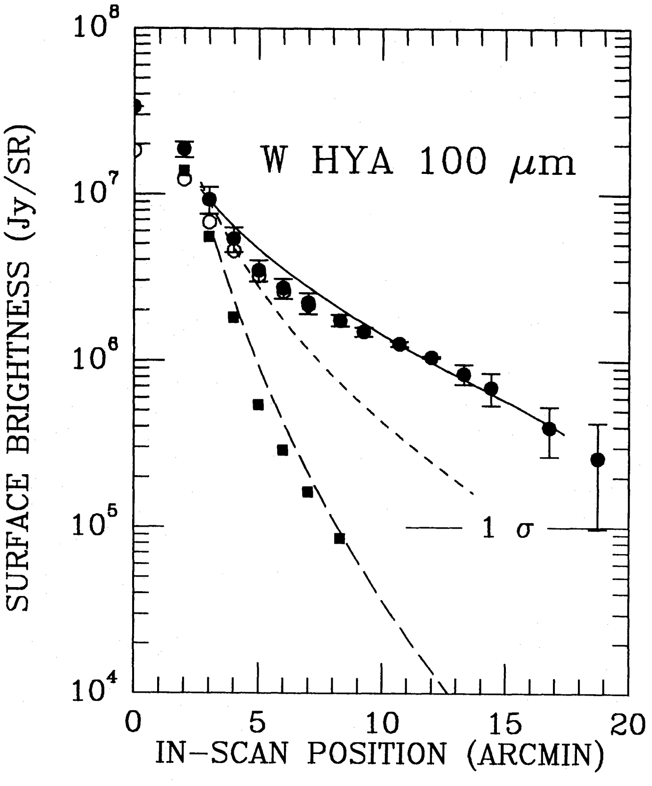

Figure 3. IRAS in-scan intensity profile $I_\nu(100\mu m)$ of W Hya (•) and IRC +10011 (squares). The open circles (○) display W Hya data after removal of inner 5" radius point source components 2 and 3 of Table 1. The solid line shows the simulated surface brightness from a spherical circumstellar dust shell for W Hya, with $\theta_{max} = 20'$, D = 130 pc, density $n(\theta) \propto \theta^{-1.0}$, dust emissivity $\epsilon \propto \nu^{1.2}$, and $\dot{M}_d(\theta = 4') = 2.7$x10^{-9} $M_\odot$. The short dashed curve shows the surface brightness for W Hya with the same parameters except $n(\theta) \propto \theta^{-2.0}$. The long dashed curve shows the surface brightness for IRC +10011, with the same parameters as W Hya except density $n(\theta) \propto \theta^{-2.0}$, D = 510 pc, and $\dot{M}_d$ = 1.7x10^{-7} $M_\odot$. The 1 sigma noise level is shown

it sweeps up its own mass is (Alcock and Illarionov, 1980) $R = 4a\rho_g/3n_{ism}m_h$, which is $\sim$ 80 pc for n_{ism} = .1 cm^{-3} with grains of radius a = .1 μm and ρ_g = 3 gm cm^{-3}. Gas densities greater than 10 cm^{-3} are required for dust grains to interact with the gas on a time scale shorter than the shell expansion time ($\sim$ 1x10^4 yrs). Therefore, unlike the dense inner envelope, grains are uncoupled from both the interstellar and circumstellar gas (where n $\leq$ 10 cm^{-3} at radius $\geq 1.5'$) in the outer envelope.

CO measurements by Wannier and Sahai (1986) are unresolved with a 25″ beam. This is consistent with a photodissociation radius ≤15″ corresponding to $\dot{M} \lesssim 3\times10^{-7}$ $M_\odot yr^{-1}$, derived from improved CO photodissociation rates of Mamon, Glassgold and Huggins (1988). However, atomic hydrogen is not photodissociated in the outer envelope, and the gaseous component of W Hya's wind may be resolved with 21 cm line observations, similar to the detection of extended 21 cm H I emission around α Ori and o Cet by Bowers and Knapp (1987 and 1988).

Why is W Hya's CSE much larger than CSEs around stars with larger dust mass loss rates ($\dot{M}_d = 10^{-6} - 10^{-7}$ $M_\odot yr^{-1}$)? Several explanations are possible. The closeness of W Hya to the Earth increases its CSE diameter by 1) greater apparent size, and 2) higher dust temperatures in the outer envelope compared to stars farther away. Dust temperatures fall more steeply with angle observed from Earth for objects at greater distances. Figure 3 shows this effect, as $I_\nu(100\mu$ m) for IRC +10011 falls more steeply with angle than $I_\nu(100\mu m)$ for W Hya, because IRC +10011 is five times farther away. Thus W Hya's infrared envelope is larger than IRC +10011's, despite IRC +10011's larger mass loss rate.

Simple models of dust emission computed from equation 2 for a large sample of evolved stars suggest that except for very nearby objects (D $\leq$ 200 pc), extended IRAS emission results not from stars with large current mass loss rates, but from stars that had greater mass loss rates in the past. Many famous evolved stars with large mass loss rates may have large CSEs which are hidden from IRAS detection because emission from density laws $n(r) \propto r^{-2}$ and steeper cannot be distinguished from the IRAS point source profiles.

In conclusion, the evolved star W Hya is surrounded by a 30′–40′ diameter (~1 pc) dust envelope radiating at 60 and 100 μm. The prominance of W Hya's envelope relative to other asymptotic giant branch stars with larger $\dot{M}$ observed by IRAS is probably due to a combination of 1) nearness of W Hya, 2) decline of $\dot{M}$ with time, 3) low ISM densities, and 4) location of W Hya out of the galactic plane. IRAS observations also reveal extended, 20′ diameter, 100 μm emission at 3 σ above noise, centered symmetrically around the oxygen-rich red giants O Cet (D = 77 pc) and RX Boo (D = 195 pc), and 30′ – 35′ diameter 3 σ emission at 60 and 100 μm around R Dor (D = 80 pc). These nearby giants are the only stars in addition to W Hya displaying such extended IRAS emission that were found in a sample of $\sim$ 150 giants with detected CO emission, and will be analyzed in a future paper.

Extended 60 and 100 μm IRAS emission offers a tool to reliably determine the total mass and diameter of CSEs, to provide clues on variable mass loss, densities, and the radiation field in the interstellar medium. Further studies are needed to better establish the heating source for dust grains in CSEs, and determine why more evolved stars with ≥ 10′ diameter CSEs are not seen. The search for other evolved stars with large CSEs will be difficult due to infrared cirrus and the high source density in the galactic plane, requiring two-dimensional IRAS maps, even for large flux objects, to verify that extended emission originates from mass loss.

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Table 1. Photometry of W Hydrae

Component	Flux densities (Jy) 12 μm	25 μm	60 μm	100 μm
1) psc flux densities (a)	3300±500	850±130	160±25	65±15
2) photosphere	1586±200	460±60	86±10	32±5
3) dust flux ≤5″ radius	1590	390	39	9
4) flux inside 30′ diameter	3300±500	850±130	220±30	142±20

a) color corrected using 1) 2200 K photosphere (blackbody) and 2) circumstellar dust (blackbody modified by dust emissivity $\propto \lambda^{-1.2}$)

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