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IRAS04496−6958: A luminous carbon star with silicate dust in the Large Magellanic Cloud*

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Abstract. We describe ISO observations of the obscured Asymptotic Giant Branch (AGB) star IRAS04496−6958 in the Large Magellanic Cloud (LMC). This star has been classified as a carbon star. Our new ISOCAM CVF spectra show that it is the first carbon star with silicate dust known outside of the Milky Way. The existence of this object, and the fact that it is one of the highest luminosity AGB stars in the LMC, provide important information for theoretical models of AGB evolution and understanding the origin of silicate carbon stars.

Key words: Stars: carbon – circumstellar matter – Stars: mass loss – Stars: AGB and post-AGB – Magellanic Clouds – Infrared: stars

1. Introduction

Asymptotic Giant Branch (AGB) carbon stars are produced following 3^{rd} dredge-up in thermally pulsing stars (e.g. Iben & Renzini 1983). The star changes from oxygen- to carbon-rich when sufficient carbon has been mixed-in with the stellar mantle to yield an abundance ratio C/O>1. The chemistry of the dust in the circumstellar envelope (CSE) changes accordingly. The change occurs at smaller core-mass — or lower luminosity — for lower metallicity stars. Clear evidence for this comes from observations of clusters in the Large Magellanic Cloud (LMC) that contain both carbon and M-type stars (Lloyd Evans 1984; Marigo et al. 1996).

Surprisingly, silicate emission from oxygen-rich dust was discovered in the IRAS Low Resolution Spectra of several galactic carbon stars (Little-Marenin 1986; Willems & de Jong 1986). Willems & de Jong interpreted these "silicate carbon stars" as direct evidence for a fast transition of M-type AGB stars into carbon stars, but timescales of decades for the silicate emission from an expanding detached oxygen-rich CSE to fade away are difficult to reconcile with the lifetimes of silicate carbon stars (Little-Marenin et al. 1987; Le Bertre et al. 1990). Hence the oxygen-rich material must be stored in a stationary component. Many galactic silicate carbon stars are ^{13}C-enhanced, J-type, carbon stars (Lambert et al. 1990). Unlike genuine, N-type, carbon stars that form on the AGB, J-type carbon stars are thought to have become carbon-enriched as a result of binary evolution. The presence of a mass-losing oxygen-rich companion star has been ruled out observationally for a number of galactic silicate carbon stars (Noguchi et al. 1990; Engels & Leinert 1994). The presently most supported explanation for the silicate carbon star phenomenon is that of a keplerian disk of oxygen-rich material, surrounding a binary including a faint companion (Lloyd Evans 1990). The oxygen-rich dust may originate from mass loss at a time when the carbon star was still oxygen rich (Lloyd Evans 1990).

The dust-enshrouded AGB star IRAS04496−6958 was recently discovered to be a luminous carbon star in the LMC by van Loon et al. (1998, 1999) on the basis of ground-based (CTIO) 3 μm spectroscopy, after having been selected and confirmed to be an AGB star by Loup et al. (1997) and Zijlstra et al. (1996), respectively. The carbon star nature of this object has been confirmed by Groenewegen & Blommaert (1998) using optical spectroscopy. At $M_{\rm bol} = -6.8$ mag it is the brightest known magellanic carbon star and very close to the maximum AGB luminosity ($M_{\rm bol} \sim -7$ mag). We here present compelling evidence for the presence of oxygen-rich dust close to this remarkable carbon star, making it the first known extragalactic silicate carbon star.

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Table 1. ISO 12, 25 and 60 μm photometry (in Jy) of IRAS04496−6958. The near-IR magnitudes are deduced from light-curves obtained at SAAO ($JD - 2,450,000 = \mathrm{orbit} + 38$), and are on the SAAO photometric system (Carter 1990). Values between parentheses are 1-σ errors.

JD	$J[mag]$	$H[mag]$	$K[mag]$	$L[mag]$	F_{12}(CAM)	F_{25}(PHOT)	F_{60}(chop)	F_{60}(map)	Spectrum
195	13.00(0.05)	10.90(0.05)	9.50(0.04)	7.70(0.04)	0.269(0.002)	0.126(0.010)	0.252(0.154)		PHOT
605	12.40(0.05)	10.40(0.05)	8.95(0.05)	7.60(0.05)					CAM (A)
905	12.90(0.10)	11.00(0.10)	9.40(0.05)	7.80(0.05)				0.223(0.123)	CAM (B)

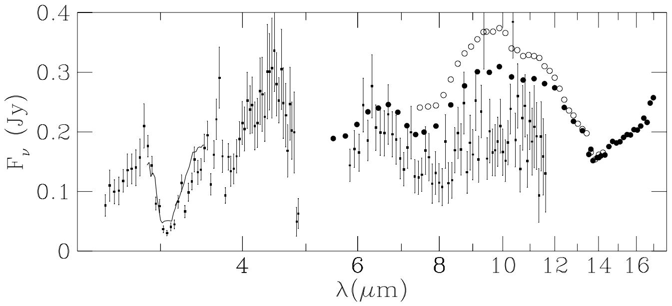

Fig. 1. IR spectra of IRAS04496−6958. The ISOPHOT spectrum is plotted with errorbars. The ISOCAM spectra A and B are plotted using open and solid circles, respectively. A 3 μm spectrum taken at CTIO on December 24, 1996 (van Loon et al. 1999) is overplotted as a solid curve, after scaling to the PHOT-S continuum level.

2. ISO observations

The spectral energy distribution (SED) of this object peaks in the infrared. Therefore in order to properly model the spectrum we obtained photometric and spectro-photometric observations with the European Infrared Space Observatory (ISO, see Kessler et al. 1996), using the ISOCAM (Cesarsky et al. 1996) and ISOPHOT (Lemke et al. 1996) instruments.

The photometric observations at 12 μm (using ISOCAM filter LW10) and 25 μm (using ISOPHOT) were obtained on April 22, 1996. The 12 μm observation was done using $3''$ pixels, and a total on-source integration time of 50 s split in 25 two-s integration intervals. The 25 μm ISOPHOT observation was done using the P2 detector, a $52''$ aperture, and triangular chopping with a chopper throw of $90''$. The on-source integration time was 64 s. The 60 μm photometry was obtained using the PHOT-C100 detector using two different methods. One observation (April 22, 1996) was done using chopping mode with triangular chops and a chopping angle of $150''$ and an on-source integration time of 64 s. Another observation (April 1, 1998) was done with a 3×3 raster map with $46''$ raster steps and an integration time per pointing of 128 s, giving an effective on-source integration time of ~ 1100 s.

Spectro-photometric observations of the source were obtained with ISOPHOT-S and the ISOCAM CVF. The PHOT-S spectrum (April 22, 1996) was done in staring mode with an on-source integration time of 512 s. Two ISOCAM CVF spectra were obtained. The first ISOCAM spectrum (June 5, 1997, hereafter "spectrum A") spans the wavelength range from 7 to 14 μm, the second (April 1, 1998, hereafter "spectrum B") from 5 to 17 μm. The $6''$ pixel field of view was used, with an integration time per spectral point of 50 and 70 s, respectively.

The data was processed using standard processing routines in the PHOT Interactive Analysis (PIA[1]) and CAM Interactive Analysis (CIA[2]) software. The CAM-CVF spectra were constructed using a 3×3 pixel^2 software aperture and applying a correction for the wavelength dependence of the point spread function. We corrected the PHOT-S spectrum for the background as derived from the CAM-CVF data, accounting for the annual modulation of the zodiacal light using COBE/DIRBE weekly all-sky maps (see also Trams et al. 1999). The photometric observations are listed in Table 1. The ISO observations are supplemented with ground-based J, H, K, and L-band observations made at the South African Astronomical Observatory (SAAO), interpolated to the same epochs as the various ISO observations.

The spectra are presented in Fig. 1. Also plotted is a spectrum around 3 μm obtained at CTIO (van Loon et al. 1999), after scaling to match the approximate continuum level in the PHOT-S spectrum. We believe that the PHOT-S spectrum longward of ~ 6 μm has been under-estimated, and possibly distorted, due to difficulties in determining the stabilised signal at such low flux density levels.

3. Discussion

3.1. Properties of the circumstellar dust of IRAS04496−6958

The PHOT-S and CTIO spectra show the strong 3 μm feature from HCN and C_2H_2 (Fig. 1), but the long wavelength part of the PHOT-S spectrum is rather noisy. The CAM-CVF spectra, however, show a prominent emission feature between 9 and 12 μm with a small dip near 11 μm. For comparison we also plot in Fig. 2 the ISO SWS spectrum ($\div 200$) of the galactic silicate carbon star V778 Cyg, taken from Yamamura et al. (1997), which shows strong silicate emission from oxygen-rich dust around 10 μm. The feature in IRAS04496−6958 extends to longer wavelengths than in V778 Cyg, and closely resembles that of another galactic silicate carbon star, CS1003 (Hen 83, IRAS08002−3803; see Little-Marenin 1986 and Willems & de Jong 1986). We also plot in Fig. 2 the ground-based UKIRT spectrum ($\div 4000$) of the galactic carbon star AFGL2368, taken from Speck et al. (1997), which shows a prominent silicon car-

[1] PIA is a joint developement by the ESA Astrophysics Division and the ISOPHOT consortium led by the Max Planck Institute for Astronomy (MPIA), Heidelberg. Contributing ISOPHOT Consortium Institutes are DIAS, RAL, AIP, MPIK and MPIA.

[2] CIA is a joint developement by the ESA Astrophysics Division and the ISOCAM consortium led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Materie, C.E.A., France.

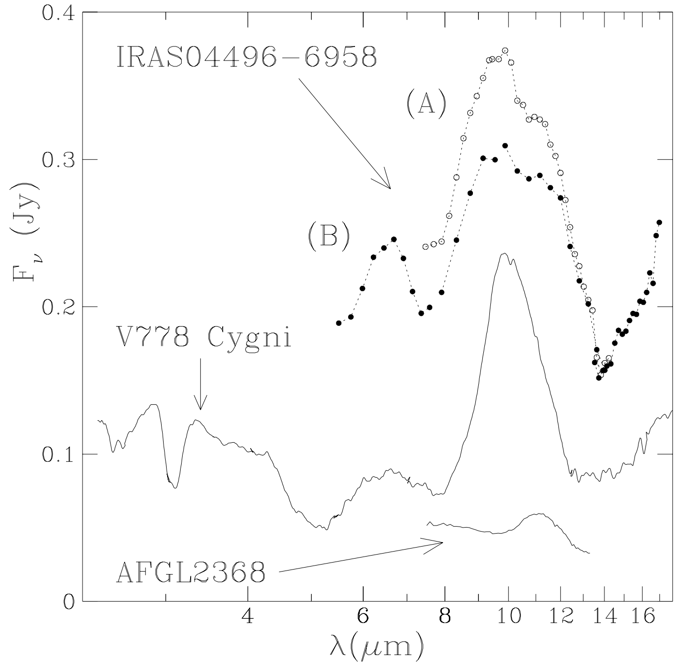

Fig. 2. The CAM-CVF spectra of IRAS04496−6958 compared to the SWS spectrum ($\div 200$) of the silicate carbon star V778 Cyg (Yamamura et al. 1997) and the UKIRT spectrum ($\div 4000$) of the carbon star AFGL2368 (Speck et al. 1997).

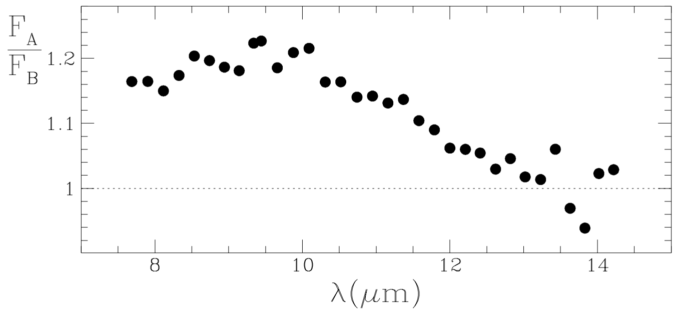

Fig. 3. The ratio of the two CAM-CVF spectra of IRAS04496−6958. The spectra are variable up to $\sim$ 13 μm, where the variability ceases because stationary dust emission becomes dominant.

bide (SiC) emission feature around $\sim$ 11.5μm that is common in carbon stars (see e.g. Little-Marenin 1986; Yamamura et al. 1997). The shape of the 9-12 μm emission feature in IRAS04496−6958 may be explained by assuming that the feature is a composition of the silicate and SiC features. Alternative explanations include large silicate grains (Forrest et al. 1975; Papoular & Pégourié 1983), crystalline olivines (Koike et al. 1981) and corundum (AlO) grains (Onaka et al. 1989). We note that similarly shaped emission is observed in the spectra of a wide variety of objects: the S star RT Sco and MS stars (Little-Marenin & Little 1988), the Sil^{+} and Sil^{++} classes of M-type Mira variables (Little-Marenin & Little 1990), β Pictoris (Knacke et al. 1993; Fajardo-Acosta & Knacke 1995), inter-planetary dust particles (Sandford 1988) and comet Halley (Campins & Ryan 1989).

Absorption against the photosphere by HCN and C_2H_2 is seen at 3.1, 3.8 and 8 μm (Fig. 1). On the long-wavelength end of the emission feature the 13.7 μm absorption due to C_2H_2 is seen, which is commonly observed in the spectra of galactic carbon stars (Yamamura et al. 1997). This absorption is seen against the dust continuum — that dominates over the photospheric continuum at these long wavelengths — indicating that the molecules are abundant throughout the dusty CSE. It is absent in V778 Cyg. This may be understood if the molecules-to-dust ratio is larger at lower metallicity, possibly because depletion of molecules into dust grains is less severe at smaller dust-to-gas ratios.

IRAS04496−6958 is a Long Period Variable with a period of $\sim$ 710 d and a K-band amplitude of $\sim$ 0.9 mag (Whitelock et al., in preparation). The two CVF spectra are taken at different phases in the lightcurve, with spectrum A closer to maximum light. Their ratio is plotted in Fig. 3. The maximum difference is reached between 9 and 10 μm, and no difference is seen for wavelengths $\gtrsim$13 μm. This suggests that a significant part of the variability around 10 μm is due to a variable emission feature, whilst beyond 13 μm non-variable dust continuum emission dominates. The CVF ratio around 10 μm is 1.2, which equals the ratio of L-band flux densities at these two epochs (the K-band flux density ratio is 1.5). This may be compared to N- (10 μm) and L-band amplitudes observed in galactic IR-bright carbon stars, $\Delta N - \Delta L = -0.48$ mag (standard deviation 0.23) (Le Bertre 1992), and oxygen stars, $\Delta N - \Delta L = 0.13$ mag (standard deviation 0.20) (Le Bertre 1993). The difference results from the fact that in carbon stars the L-band includes variable HCN+C_2H_2 absorption, whereas in oxygen stars the N-band includes variable silicate emission. The $\Delta N - \Delta L \sim 0$ mag of IRAS04496−6958 suggests a contribution of silicate emission to the variability in the N-band. The 10 μm variability of IRAS04496−6958 is additional evidence for the silicate carbon star nature of this star, and 10 μm variability might provide a new means for finding or confirming silicate carbon stars.

All IR colours between 1 and 25 μm of IRAS04496−6958 are similar to those of carbon stars (van Loon et al. 1998; Trams et al. 1999), whereas V778 Cyg has colours (Chen et al. 1998) more similar to oxygen-rich stars. Hence the oxygen-rich dust component represents only a minor fraction of the total dust mass that is contained in the CSE of IRAS04496−6958. Its CSE is considerably thicker than that of known galactic silicate carbon stars, judged from its very red near-IR colours (Lloyd Evans 1990; Chan & Kwok 1991). Hence the observation that all galactic silicate carbon stars are of J-type (Lambert et al. 1990) may be an observational bias against N-type carbon stars with massive carbon-rich CSEs for which an optical spectrum to determine the $^{13}C/^{12}C$ ratio is relatively difficult to obtain.

3.2. The origin of the oxygen-rich dust around the carbon star IRAS04496−6958

IRAS04496−6958 is special because with $M_{\rm bol} = -6.8$ mag it is a very luminous carbon star (van Loon et al. 1998, 1999). The popular scenario for the formation of silicate carbon stars in which a J-type carbon star evolves from a less massive R-type star (Lambert et al. 1990) implies that silicate carbon stars should not be very luminous, which has some observational support (Barnbaum et al. 1991). Therefore, IRAS04496−6958 could be a different class from the galactic silicate carbon stars.

Nuclear burning at the base of the convective envelope ("Hot Bottom Burning", HBB) reduces the carbon abundance of the mantle by cycling it into nitrogen (Iben 1981; Iben & Renzini 1983; Wood et al. 1983). Theoretical models show that it occurs for the most massive AGB stars (Blöcker & Schönberner 1991). Boothroyd et al. (1993) predict that HBB prevents the occurence of carbon stars above $\rm M_{bol} = -6.4$ mag, consistent with the observed absence of optically bright carbon stars more luminous than $\rm M_{bol} \sim -6$ mag (Iben 1981; Costa & Frogel 1996). The existence of luminous dust-enshrouded carbon stars (van Loon et al. 1999) like IRAS04496−6958 in the LMC and IRAS00350−7436 in the SMC ($M_{\rm bol} = -6.6$ mag; Whitelock et al. 1989) is explained by mass loss reducing the stellar mantle to below a critical mass required for the pressure and temperature at the lower convective boundary to be sufficiently high to support HBB (Boothroyd & Sackmann 1992). If such a star experiences another thermal pulse and accompanying dredge-up of carbon to its surface, it may become a carbon star, after all (Frost et al. 1998; Marigo et al. 1998). Hence, IRAS04496−6958 has been an oxygen-rich star not longer than a thermal pulse interval of $\sim 10^4$ yr ago (see Vassiliadis & Wood 1993). This does not exclude the possibility that emission from the oxygen-rich dust is still observable around the recently formed carbon star, but the massive carbon-rich CSE around IRAS04496−6958 suggests a relatively long lapse of time since the mass loss was oxygen rich. Although the ISOPHOT 60 μm photometry is rather inaccurate, the high 60 μm flux density of IRAS04496−6958 suggest that its mass-loss rate was higher in the past, some 10^{3-4} yr ago, which would be consistent with an episode of increased mass loss during a thermal pulse followed by a considerable period of mass loss at a more moderate rate.

Hence it remains to be seen whether the silicate carbon star nature of IRAS04496−6958 requires a companion star to have captured the oxygen-rich material in a circumbinary disk, or whether it resulted from single star evolution of a massive AGB star.

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