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Silicate and ice emission bands in the *ISO* spectrum of the PAH-emitting carbon-rich planetary nebula CPD −56°8032

Martin Cohen

Radio Astronomy Laboratory, University of California, Berkeley, CA 94720, U.S.A.

M. J. Barlow, R. J. Sylvester, X.-W. Liu

Dept. of Physics and Astronomy, University College London, London WC1E 6BT, U.K.

P. Cox

Institut d'Astrophysique Spatiale, Université de Paris XI, F-91405 Orsay Cedex, France

T. Lim

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK

B. Schmitt

Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS, F-38041 Grenoble/Saint Martin d'Hères, France

A. K. Speck

Dept. of Physics and Astronomy, University College London, London WC1E 6BT, U.K.

Abstract. Combined ISO SWS and LWS spectroscopy is presented of the late WC-type planetary nebula nucleus CPD −56°8032 and its carbon-rich nebula. The extremely broad coverage (2.4–197 μm) enables us to recognize the clear and simultaneous presence of emission features from both oxygen- and carbon-rich circumstellar materials. Removing a smooth continuum highlights bright emission bands characteristic of polycyclic aromatic hydrocarbons (hereafter PAHs) in the 3–15 μm region, bands from crystalline silicates longwards of 18 μm, and the 43- and 62-μm bands of crystalline water ice. We discuss the probable evolutionary state and history of this unusual object in terms of (a) a recent transition from an O-rich to a C-rich outflow following a helium shell flash; or (b) a carbon-rich nebular outflow encountering an O-rich comet cloud orbiting in a Kuiper-belt-like distribution.

1. Introduction

CPD –56°8032 (hereafter CPD) belongs to the rare class of late WC-type ([WCL]) nuclei of planetary nebulae (PNNs). These objects may result when a helium shell-flash in a low- or intermediate-mass star on the Asymptotic Giant Branch (AGB) either ingests or ejects all the remaining hydrogen-rich outer envelope, leaving a H-poor, carbon-rich star spectrally like late WC-type population I Wolf-Rayets.

CPD's large infrared excess has long been attributed to dust emission (Webster & Glass 1974; Cohen & Barlow 1980). PAH bands also appear in emission (Aitken et al. 1980; Cohen, Tielens & Allamandola 1985; Cohen et al. 1989). CPD has the highest measured IR luminosity fraction in the 7.7-μm band of any object (Cohen et al. 1989), consistent with its very large nebular gas-phase C/O number ratio of 13 (De Marco, Barlow & Storey 1997; hereafter DMBS).

We present Infrared Space Observatory (ISO) Long Wavelength Spectrometer (LWS; Clegg et al. 1996; Swinyard et al. 1996) 43–197 μm full grating spectra of CPD, combined with Short Wavelength Spectrometer (SWS; de Graauw et al. 1996) 2.4–45 μm grating spectra of this object, obtained in the LWS Guaranteed Time program. Barlow (1998) has summarized our preliminary ISO results on CPD.

2. The ISO spectrum of CPD -56°8032

Full wavelength coverage grating mode LWS01 spectra of CPD were secured in eight fast scans, each comprising a 0.5-s integration ramp at each grating position, sampled at 1/4 of a spectral resolution element. Our low-resolution 2.4–45 μm SWS grating spectrum of CPD was taken at Speed 1, yielding a mean spectral resolving power of ~250. Standard pipeline processing (LWS OLP6.0 and SWS OLP6.1) was used to extract, reduce and calibrate the separate subspectra. The ISAP and SIA packages provided the capability to examine the spectral fragments in detail.

Fig. 1 presents our complete wavelength coverage of CPD. We first spliced all the SWS and LWS subspectra separately, following the methods described by Cohen, Walker & Witteborn (1992; CWW), then joined the composite SWS and LWS portions, which required scaling the LWS spectrum by 0.99±0.01 to register it with the SWS spectrum. The resultant 2.4–197 μm spectrum was normalized to the Point Source Catalog (PSC) photometry (see CWW) in all 4 IRAS bands, necessitating a further rescaling of the total spectrum by 1.05±0.04.

The ISO spectrum of CPD in Fig. 1 exhibits the canonical spectrum of PAH emission bands but the most striking aspect is that, despite the carbon-dominated stellar and nebular chemistry, the spectrum longwards of 15 μm is dominated by emission features usually associated with the circumstellar envelopes of O-rich stars (Glaccum 1990; Waters et al. 1996). Waters et al. (1998a, b) have presented SWS spectra of several other C-rich post-AGB objects, also with both PAH and crystalline silicate emission features. The ISO spectrum of CPD has an additional remarkable property in that crystalline water ice features are present in emission at 43 and 62 μm (see below).

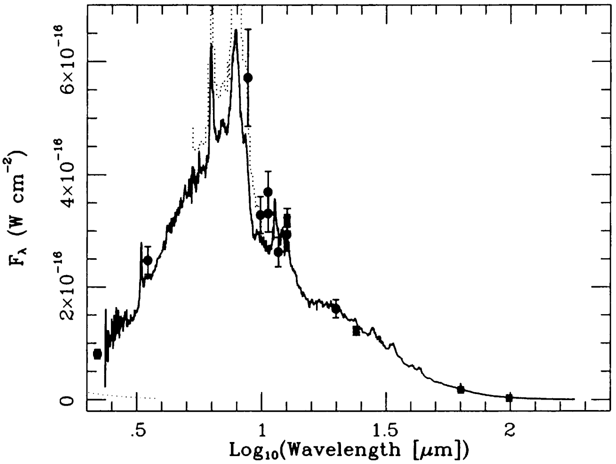

Figure 1. Full SWS+LWS spectrum of CPD-56°8032 (heavy solid line). Also shown are IRAS PSC fluxes (filled squares, plotted at their isophotal wavelengths), the 2–20 μm photometry of Cohen & Barlow (1980, filled circles), and (as dotted lines) the 5–8 μm KAO spectrum of Cohen et al. (1989) and the 7.7–22.7 μm IRAS LRS spectrum.

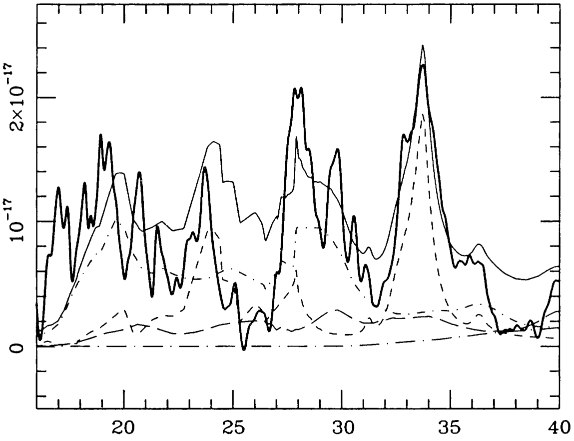

Figure 2. The emission from CPD-56°8032 in excess of the two-blackbody continuum, from 16–40 μm. Heavy solid line: observed excess emission; short-dashed line, forsterite; long-dashed line, clinopyroxene; short-dash dotted line, orthopyroxene; long-dash dotted line, crystalline ice; light solid line, the sum of all these components. The units of excess flux are W cm^{-2} μm^{-1}.

To amplify the intensities of the many emission bands, we subtracted a continuum as the sum of two blackbodies (temperatures and solid angles optimized by least-squares fit to the lower envelope of the observed spectrum). The best fit is for temperatures of 470±5K and 135±5K. Fig. 2 illustrates a portion of CPD's "excess" spectrum. Between 16 and 40 μm (Fig. 2), emission features characteristic of crystalline silicates are seen prominently at 19, 24, 28, and 33 μm. The longer wavelength region (not shown) exhibits emission bands at 41, 43, 48, and 69 μm, along with a very broad, low-level, emission hump centered near 62 μm, under the [O I] 63-μm line. We identify the 43- and 62-μm bands with crystalline water ice, as first detected by Omont et al. (1990) in the KAO spectrum of the Frosty Leo nebula.

We have attempted to identify the emission features seen above the continuum of CPD using data for clinopyroxene, orthopyroxene and 100% forsterite (Koike et al. 1993) and optical constants for both amorphous and crystalline water ice recently measured in the laboratory (Trotta 1996; Schmitt et al. 1998). Only 100% pure forsterite shows the 69 μm feature (Koike et al. 1993). Fig. 2 distinguishes the separate contributions of these four materials, and their total. We modeled the optically thin case, for small spherical grains (0.1 or 1.0 μm radius) and, by matching relative band strengths, we found plausible temperatures (forsterite, clinopyroxene, and crystalline ice: 65 K; orthopyroxene: 90 K), suggestive of a common physical location. The cold silicates produce no measurable emission below the 19-μm band. Without combined SWS+LWS coverage, one cannot constrain these temperatures.

Modelling indicates that: forsterite causes the 24- and 33-μm bands; crystalline silicates such as orthopyroxene the 19- and 28-μm bands; crystalline ice the 43- and 62-μm features; and clinopyroxene the prominent 41-μm band and part of the broad 66-μm emission feature. It is striking that CPD displays both carbon- and oxygen-rich materials and that its materials are so much more ordered (crystalline) than the laboratory data.

3. Discussion

From the luminosity and distance of CPD (1.5 kpc: DMBS), we can deduce the angular extent of each of the emitting dust components, summarized in Table 1. The diameter of the 3.3-μm PAH emission is from Roche, Allen & Bailey (1986) and the ionized zone from HST Hβ imaging (see DMBS).

The black grains are probably carbon-rich, like the dust that forms in the outflows from Population-I WC9 stars (e.g., Cohen, Barlow & Kuhi 1975). The crystalline materials seem to exist just outside the ionized zone while the PAHs appear within the ionized region. Other [WCL] PNe show the signatures of both C-rich and O-rich material, e.g. the [WC10] PNN IRAS 07027–7934 (Menzies & Wolstencroft 1990) with PAH features and a 1612 MHz OH maser (Zijlstra et al. 1991); the Type I bipolar PN NGC 6302 with weak 8.7- and 11.3-μm PAH bands (Roche & Aitken 1986), a weak OH maser (Payne, Phillips & Terzian 1988), and ice and crystalline silicate features (Barlow 1998; Waters et al. 1996); and the [WCL] PNNs BD +30°3639 and He 2-113 (Waters et al. 1998a, b).

If a recent thermal pulse converted an O-rich mass loss outflow to a C-rich one, then why do we observe over 6 [WCL] PNNs in the same evolutionary state

Table 1. Cross-section through CPD's different zones.

Material	Temperature K	Mass $10^{-4}M_\odot$	Ang. diam. arcsec	Diameter AU
Hot grains	1600	–	?	~few
BB	470	–	0.06	80
BB	135	–	0.7	1 000
3.3 μm PAHs	–	–	1.3	2 000
ionized gas	–	–	1.6×2.1	2 400×3 000
forsterite	65	1.6	2	3 000
clinopyroxene	65	1.3	2	3 000
orthopyroxene	90	0.3	2	3 000
crystalline ice	65	0.6	2	3 000

when such a transition should occur only once during the lifetime of a star? This seems even less probable when one estimates that the O-rich grains must have been ejected only 250 yr ago by CPD (the nebular expansion velocity is 30 km s^{-1} (DMBS) and this material is now 1" from the star), such a tiny fraction of the 6×10^4 yr interpulse interval (for a 0.62 $M_\odot$ core: Boothroyd & Sackmann 1988). Waters et al. (1998a) suggest that such stars are somehow particularly susceptible to a thermal pulse during their immediate post-AGB phase.

An alternative possibility is that the crystalline ice and silicates are pre-existing, and residing in a Kuiper belt or inner Oort comet cloud around CPD. The radius of 1500 AU is comparable to current estimates for the outer edge of the Kuiper belt around our own Sun (Weissman 1995). The interaction of cometary nuclei in such a belt with CPD's mass outflow and ionization front could provide the conditions needed to liberate the small particles ($< 3-10\ \mu$m radius) that are required in order to explain the observed far-infrared silicate and ice bands. It is, therefore, of particular interest to note the presence of the same bands in the ISO spectrum of Comet Hale-Bopp (Crovisier et al. 1997). The annealing and recrystallization of silicates and ice grains liberated from comets, leading to the required highly ordered structures with correspondingly "sharp" emission features, may have resulted from the sudden increase in the UV photon flux from CPD during its post-AGB evolution.

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