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Letter to the Editor

Crystalline silicates in planetary nebulae with [WC] central stars*

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Abstract. We present ISO-SWS spectroscopy of the cool dusty envelopes surrounding two Planetary Nebulae with [WC] central stars, BD+30 3639 and He 2-113. The $\lambda < 15$ μm region is dominated by a rising continuum with prominent emission from C-rich dust (PAHs), while the long wavelength part shows narrow solid state features from crystalline silicates. This demonstrates that the chemical composition of both stars changed very recently (less than 1000 years ago). The most likely explanation is a thermal pulse at the very end of the AGB or shortly after the AGB. The H-rich nature of the C-rich dust suggests that the change to C-rich chemistry did not remove all H. The present-day H-poor [WC] nature of the central star may be due to extensive mass loss and mixing following the late thermal pulse.

Key words: Infrared: stars – stars: AGB and post-AGB; mass loss – planetary nebulae - dust

1. Introduction

Planetary Nebulae (PNe) are the ionized and photodissociated remnants of extensive mass loss which the central star experienced when it was a cool Asymptotic Giant Branch (AGB) star. PNe therefore provide insight in the mass loss on the AGB and beyond. An interesting class of PNe are those with a Wolf-Rayet ([WC]) central star. These central stars have strongly enhanced C and He, but little or no H in their atmosphere, and are the low mass counterparts to the population I Wolf-Rayet stars. About 50 [WC] stars are known (Gorny & Stasinska 1995). The properties of these nebulae do not differ significantly from nebulae with 'normal' central stars (Pottasch 1996).

The formation of H-poor central stars is somewhat of a puzzle, but is probably related to a thermal pulse either at the very end of the AGB or young PN phase (in this paper referred to as PAGB pulse; Zijlstra et al. 1991), or when the star is already on the cooling track (very late thermal pulse; Iben 1984). The H-rich layers may be removed due to efficient mixing and subsequent nuclear burning, or by extensive mass loss, exposing processed layers to the surface. Examples of objects that may have recently experienced a late thermal pulse are FG SGe and Sakurai's object (e.g. Paczyński 1970; Nakano et al 1996; Duerbeck et al. 1996; Blöcker & Schönberner 1997). It is not clear that these stars will develop [WC] type spectra.

IR spectroscopy of the dust ejected by [WC] central stars shows the well-known family of IR emission bands, usually identified as due to Polycyclic Aromatic Hydrocarbons (PAHs) (e.g. Cohen et al. 1986). This confirms the C-rich nature of the most recent mass loss episode. In this *Letter*, we present new infrared spectra taken with the Short Wavelength Spectrometer (SWS) on board of the Infrared Space Observatory (ISO) of two well-studied PNe with [WC] central stars, BD+30 3639 and He 2-113. Both nebulae have associated molecular gas (Taylor et al. 1990; Bachiller et al. 1991; Gussie & Taylor 1995). In Sect. 2, we discuss the observations and data reduction, Sect. 3 gives an inventory of the solid state features (both C-rich and O-rich). In Sect. 4 we present a first attempt to model the dust spectrum of BD+30 3639, and we discuss these results in the context of post-AGB evolution and formation scenarios for [WC] central stars of PNe.

2. The observations

Full scans (AOT01 speed 1 and 2, λ 2.4-45 μm) of BD+30 3639 ([WC9]) and He 2-113 ([WC11]) were obtained using the SWS (de Graauw et al. 1996) on board of ISO (Kessler et all. 1996), as part of a guaranteed time programme on spectroscopy of PNe (p.i. D.A. Beintema). The spectra were taken on Nov. 6, 1996 (BD+30 3639) and February 4, 1996 (He 2-113), and were reduced using version 5.3 of the SWS off-line analysis pipeline. All detector signals were inspected for spurious jumps and glitches, and in two cases removed manually. The spectra of the 12 individual detectors in each SWS AOT band were sigma-clipped, averaged and re-binned to a uniform resolution

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of 250. Finally, the different AOT bands were joined together to form a continuous spectrum. For He 2-113 we did not need to adjust individual AOT bands, but for BD+30 3639 we reduced the fluxes measured in bands 3E and 4 (wavelengths of 27.5 microns and longer) by 17 per cent. This is within the absolute flux calibration uncertainties (Schaeidt et al. 1997). Jumps in flux can occur at 27.5 and 29.0 microns, where the effective aperture changes from 14*27 to 20*27 and 20*33 arcsec). The jump seen in BD+30 3639 could be caused by the finite extent of the nebula (10 arc sec or less in the optical, Harrington et al. 1997); Cox et al. (1997, in preparation) find that the extent of the neutral envelope is twice that of the ionized nebula. Flux jumps can also be due to a small pointing error. The good agreement with the IRAS-LRS spectrum (not shown) excludes a serious pointing error. The resulting spectra are plotted in Fig. 1, and in Fig. 2 we plot continuum subtracted spectra for both objects. The location of the continuum was estimated by eye. This procedure may underestimate the contribution from weak, broad features that are not easily distinguishable from the smooth underlying continuum. However narrow (width less than a few μm) features are well preserved.

3. Solid state features

Here we discuss the solid state features in our SWS spectra. A full description of the atomic and ionic emission lines will be given elsewhere.

The short wavelength part of the spectra of both stars is dominated by prominent emission from the well-known family of IR emission bands, usually attributed to Polycyclic Aromatic Hydrocarbons (PAHs) (e.g. Léger & Puget 1984). PAHs in BD +30 3639 were previously reported by e.g. Witteborn et al. (1989), Allamandola et al. (1989), and Cohen et al. (1986, 1989). The overall shape of the PAH bands is similar in both objects (Fig. 2). The plateau at 11-14 μm is very prominent in BD+30 3639, but does not extend as far to the red as in IRAS21282+5050 (Beintema et al.1996; Molster et al. 1996). This plateau is attributed to a blend of many bands due to deformation modes of large PAH molecules. As in IRAS21282+5050, we find prominent 12.0 and 12.7 μm features. These latter bands may be attributed to C-H bending modes in PAH molecules with 2 or 3 adjacent H atoms attached (Allamandola et al. 1986). This evidence of H in the C-rich dust shell is consistent with a recent determination of the photospheric H abundance in He 2-113 (7 per cent, Leuenhagen & Hamann 1997), although a quantitative comparison of the present-day photospheric H abundance and the H content of the C-rich dust shell is difficult to make. The PAHs in BD+30 3639 suggest that also in that star H was present in the C-rich phase.

In both objects, the spectrum at $\lambda > 20$ μm shows weak, and narrow solid state features, whose strength is of the order of 10 per cent of the local continuum (Fig. 2). These solid state features are observed in the spectra of *oxygen-rich* (proto-) planetary nebulae and red AGB stars (Waters et al. 1996; Justtanont et al. 1996). Following Waters et al. (1996) we identify the features at 19.8, 23.5, 27.5 and 33.8 μm with crystalline

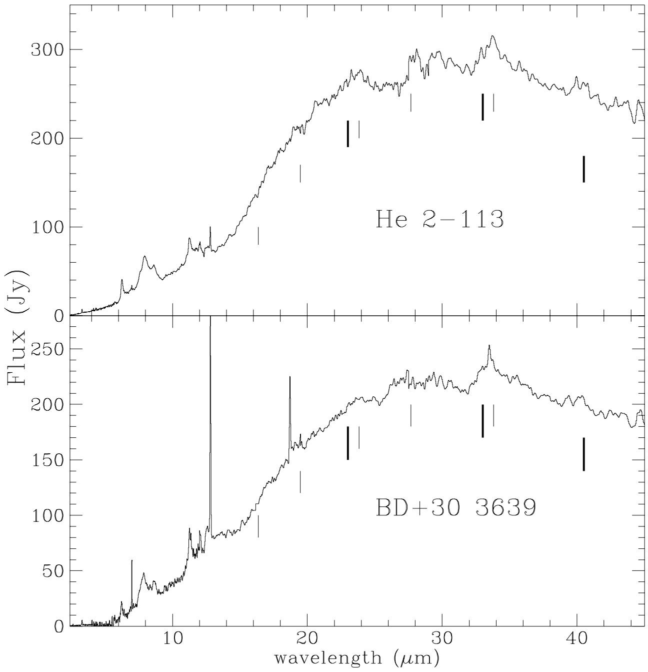

Fig. 1. 2.4-45 μm ISO-SWS spectra of He 2-113 and BD+30 3639, showing the PAH emission features at $\lambda < 13$ μm and the crystalline silicates at $\lambda > 20$ μm. Tickmarks indicate olivine bands (short thin lines; Dorschner, private communication) and pyroxene (long thick lines; Koike et al. 1993). Emission from [Ne II] at 12.8 μm is seen in both nebulae, and from [Ar II] at 6.99 μm, [S III] at 18.71 μm, and [Si II] at 34.8 μm in BD+30 3639.

olivine (Koike et al. 1993; Dorschner, private communication). The peak at 40.5 μm is due to crystalline pyroxenes (Koike et al. 1993; Dorschner, private communication; Jäger et al. 1994). The pyroxenes also contribute to the peaks at 23 μm and 33 μm. The band strength ratio of the 23.5 and 33.8 μm bands of BD+30 3639 and He 2-113 (0.5 and 1 respectively) suggests that the crystalline dust in He 2-113 is warmer than that in BD+30 3639 (assuming similar dust composition). This is consistent with the slope of the continuum. We conclude that both [WC] stars experienced strong mass loss as an O-rich star at the end of the AGB, and that the change to C-rich chemistry immediately followed. The O-rich nature of the outer layers of the BD+30 3639 nebula can explain the high albedo of the scattering particles in the halo surrounding the ionized inner nebula (Harrington et al. 1997).

4. Discussion

4.1. A dust model

The presented model is calculated using the dust radiation transfer code MODUST (de Koter et al. in preparation). We have modeled the SWS spectrum of BD+30 3639 using a two component dust model, of which the inner and outer shell connect. The inner part contains amorphous carbon grains and we have constrained the radial dimensions of this shell by requiring that it coincides with the region from which PAH emission is observed (Bernard

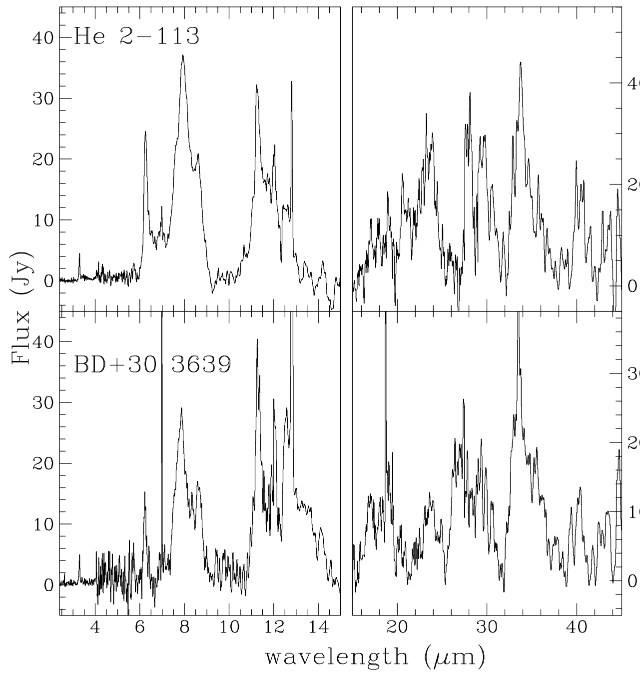

Fig. 2. Continuum subtracted 2.4-45 μm spectra of He 2-113 (top) and BD+30 3639. Notice the prominent UIR emission bands at 3.3, 6.2, 7.7, 8.6, and 11.3 μm, often attributed to Polycyclic Aromatic Hydrocarbons. At longer wavelengths emission from crystalline silicates is found (olivines, pyroxenes).

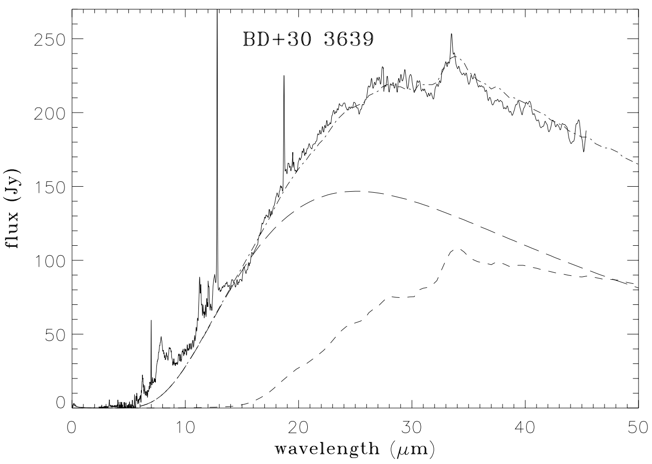

Fig. 3. Model fit to the ISO-SWS spectrum of BD+30 3639. The long dashed line is the C-rich dust shell, the short-dashed line represents the O-rich detached shell; The dash-dotted line is the sum of both components

et al. 1994), i.e. from about 1.9" to 2.7". Adopting a distance of 2.6 kpc (Hajian & Terzian 1994), this yields an inner and outer radius of the C-rich shell of 7.3 10^{16} and 10.6 10^{16} cm respectively. The luminosity of BD+30 3639 was set to 22,000 $L_\odot$ and its effective temperature to 34.2 kK. Both these values are derived from the analysis of Siebenmorgen et al (1994) after scaling to our (larger) adopted distance. Note that $T_{\rm eff}$ is rather uncertain as estimates of this value range from 30 kK (Siebenmorgen et al. 1994) to 47 kK (Leuenhagen et al. 1996). The stellar luminosity yields a current mass M = 0.89 $M_\odot$ (Paczyński 1970), neglecting the possible effects of hot-bottom burning.

Radiative transfer in the inner dust region is properly taken into account and the emerging spectrum is used to irradiate the outer shell. The outer shell is assumed to be optically thin. Feedback from the outer to the inner shell has not been taken into account, which is a valid assumption as the O-rich outer shell is optically thin at all wavelengths. The outer shell contains a mixture of amorphous and crystalline silicates. We use olivine (Dorschner, private communication), ortho-pyroxene and clino-pyroxene (Koike, private communication), and amorphous silicates (Draine & Lee 1984) with 12, 1, 2 and 85 per cent abundance respectively (by mass), and a grain size radius of 0.2 μm (0.25 μm for the amorphous silicates). The outer radius of the O-rich shell is 4.4 10^{17} cm, but is poorly constrained by the model.

The resulting model fit is shown in Fig. 3. Note that our solid state model does not yet include all structures seen in the spectrum; this will improve with better laboratory data. We find mass-loss rates for the C-rich and O-rich shells of 2 10^{-5} and 8 10^{-5} $M_\odot$/yr respectively, assuming a gas over dust ratio of 100 in both shells. The errors in the mass loss are at least a factor of two. Reasons for this large uncertainty are, among others: *(i)* the poorly known gas/dust ratio, *(ii)* the sensitivity of $\dot{M}$ to the grain size distribution function (we adopt grain sizes from 0.008 to 0.1 micron for the amorphous carbon in the inner shell and constant values in the outer shell), *(iii)* the sensitivity of the emission of the O-rich material to the internal nebular extinction from the C-rich dust (and the ionized gas).

The uncertainty in mass loss also reflects on the accuracy of the derived masses, which are $\sim$ 0.01 and $\sim$ 0.37 $M_\odot$ for the inner and outer shell respectively. The O-rich shell mass is even more uncertain, as it depends also on the poorly constrained outer boundary radius. The inner radius of the O-rich shell corresponds to a dynamical age of 1050 yr, assuming an expansion velocity of 22 km/sec (Acker et al. 1992). Taking the O-rich mass at face value, this would imply that this shell has been ejected over a time period of approximately 5000 yr. This is considerably shorter than the typical inter-puls period. The mass loss in the O-rich shell is characteristic for OH/IR stars. It may be usefull to search for OH maser emission, as one expects that OH emission remains significant until $\sim$ 1000 to 1500 yr after the end of the AGB.

4.2. The evolution of [WC] stars

The SWS spectra shown here demonstrate that both BD+30 3639 and He 2-113 were O-rich very recently. The age of the O-rich AGB remnant ($\sim$ 1050 yrs in BD+30 3639, and possibly less for He 2-113) and the mass of the C-rich envelope in BD+30 3639, suggest that the change to C-rich chemistry was triggered by a PAGB pulse and not by a very late thermal pulse. The mass contained in the C-rich dust shell of BD+30 3639 is of the same order of magnitude as the sum of the H and He layers in a young post-AGB star (Blöcker et al. 1997). This suggests that the PAGB pulse triggered the removal of the entire outer layer of the star, exposing the He- and C-rich inner layers. Evolutionary calculations of Blöcker & Schönberner (1997) show that in a PAGB thermal pulse, no efficient mixing of the H-rich envelope into the He-burning layers is expected, and hence no [WC] star would form. Only in the case of very late thermal pulses, when the central star is already on the cooling track, mixing of H into the He burning layers efficiently removes H, due to the strongly reduced envelope mass. Since the observations are not consistent with a very late thermal pulse for these two nebulae, we suggest that a PAGB thermal pulse is capable of mixing H and He-rich layers, i.e. contrary to the findings of Blöcker & Schönberner (1997).

Recent calculations of Herwig et al. (1997) suggest that a better treatment of convective mixing may result in intershell abundance patterns consistent with the surface C, O, and He abundances of [WC] central stars (see also Leuenhagen & Hamann 1997). The latter authors show that late type [WC] stars have small amounts of H and N, which may result from substantial mixing of H and He-rich layers. It is likely that the thermal pulse which caused the change in chemistry is responsible for this mixing.

The production of [WC] central stars with O-rich outer shells obviously requires fine-tuning of the timing of the last thermal pulse, either at the very end of the AGB or shortly thereafter. Zijlstra et al. (1991) discovered OH maser emission from IRAS07027-7934, demonstrating that the cool dust is O-rich. Barlow (1998) shows SWS and LWS spectra of CPD-56 8032, also with O-rich dust. This implies that O-rich cool dust is not unusual in nebulae with [WC] central stars. We note that there is evidence that very late thermal pulses can also produce nebulae with [WC] central stars. Pollacco & Hill (1994) claimed that the [WC11] star 17514−1555 (PN012.2+04.9) is surrounded by both a very compact nebula and an extended, low density nebula, consistent with a very late thermal pulse. This is one of the few late-type [WC] stars which is relatively faint in the IRAS bands. It is unclear at present which mechanism (PAGB thermal pulse with change in chemistry or very late thermal pulse) dominates the formation rate of PNe with [WC] central stars.

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