Solid state components of varying composition in the outflow of the Red Rectangle

F. Kemper
University of Virginia, PO Box 3818, Department of Astronomy, Charlottesville, VA 22903-0818

J.D. Green
Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627

E. Peeters
NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035

Abstract. We present high resolution Spitzer spectroscopy of several pointings in the outflow of the Red Rectangle. Besides the resonances due to the C-rich PAHs, the spectra show a wealth of new emission bands, in particular in the 13–19.5 µm range. We argue that these bands are due to solid state components, and show that simple oxides of a varying composition show a good match to the data. The presence of these O-rich species in the supposedly C-rich outflow is unexplained.

1. Introduction

The Red Rectangle (HD 44179) is a nearby (710 pc; Men’shchikov et al. 2002) post-Asymptotic Giant Branch (AGB) star. The post-AGB phase is a relatively short-lived phase (10^4–10^5 years; Van Winckel 2003) in the post-Main-Sequence evolution of stars with M < 8M⊙ during which the central star sheds its dusty circumstellar shell. The Red Rectangle is known to contain a central binary system (Cohen et al. 1975). Its close distance and rare evolutionary status makes the Red Rectangle a host for many phenomena not observed elsewhere in the Galaxy. It is for instance the only stellar source exhibiting the Extended Red Emission (ERE; Van Winckel et al. 2002). The Red Rectangle is also known to show a complex circumstellar chemistry. Using the Infrared Space Observatory (ISO) Waters et al. (1998) showed that both silicates and polycyclic aromatic hydrocarbons (PAHs) are present in the nebula. The oxygen-rich silicates are thought to be located in the circumbinary disk, while the carbon-rich PAHs are found in the significantly less dense bipolar outflows. The spectrometers onboard ISO lacked the resolution to confirm this theory, but ground-based observations (Miyata et al. 2004) support the idea that the PAHs are predominantly present in the outflow. Imaging obtained with the Hubble Space Telescope (HST) shows that the outflows have an inhomogeneous structure, probably reflecting variations in the density (Cohen et al. 2004). These different densities may give rise to a variation in dust condensates in the outflows. We observed the northern
outflow with the Infrared Spectrograph (IRS) onboard the Spitzer Space Telescope to look for compositional variations in the dust. Although ground-based observations do have better spatial resolution, they lack the sensitivity of the IRS.

2. Observations

We performed IRS high resolution spectroscopy on three positions in the outflow of the Red Rectangle. The positions were chosen in the northern outflow, about 30'' away from the central star (see Fig. 1). Observations were done in IRS staring mode, with integration times of 62.92 seconds for the short high (SH) observations and 58.72 seconds for the long high (LH) observations. In this work we will only discuss the SH data, since substantial calibration difficulties with the LH data still exist.

The S10.5 standard pipeline data were reduced using SMART [Higdon et al. 2004], with the remark that extended source calibration is still primitive.

Figure 1. The panel on the left hand side shows the slit positions of the IRS high resolution modules on the outflow of the Red Rectangle. The small boxes outline the positions of the SH module, and the large boxes the slit of the LH module. The solid and dashed lines indicate the two nod positions in each pointing. The positions A, B, and C are explained in the main text. On the right hand side, full slit spectral extractions in SH of each of the nods in A, B and C are presented.

3. Spectral features

Fig. 1 shows the full slit spectral extractions of each of the six positions, for the SH module. The spectra are incredibly rich, with significant variations between the different pointings. Shortwards of 13 \( \mu \text{m} \) the spectra are dominated by out-of-plane (OOP) bending modes of the PAHs [Hony et al. 2001]. Longwards of
13 µm broad emission bands dominate the spectrum, hereafter referred to as the MIR bands. They are comparable in strength to the OOPs, or in some cases even stronger. It was a surprise to see these bands, as there is no sign of similar spectral structure in the ISO spectroscopy (Waters et al. 1998), nor do we see such bands anywhere else. The carrier is unknown.

The MIR bands have some peculiar properties. First of all, the bands are very strong compared to the OOP bending modes in PAHs, thus making an identification with PAH-like species virtually impossible. Longwards of 13 µm PAHs do show spectral features like the PAH plateau (Van Kerckhoven et al. 2000) but these resonances are weak compared to the OOPs. Additional properties suggest that the carrier of the bands is a solid state condensate: the resonances are very wide, and the peak positions are shifting from position to position, perhaps due to a change in grain properties or composition. The bands are very strong compared to the continuum.

Figure 2. Identification of the MIR bands. The left panel shows a subslit extraction of one of the nod in position A. Prominently present is the 17.5 µm feature. Overplotted, and in the top part of the plot are the opacities of some Fe-Mg-oxides for comparison. The right hand panel shows subslit extractions of one of the nods of position B. The three different curves in the lower part of the plot indicate three equidistant subslit extractions, and the top part shows how the 16.5 micron MgO feature shifts to longer wavelengths when iron replaces the magnesium.

Not many dust components are known to show resonances in this wavelength range. We found that besides PAHs no materials normally found in carbon-rich environments show resonances with the properties described above. On the other hand, some oxygen-rich components are known to have resonances somewhere in the 13-20 µm range, which are detected in some astrophysical environments. A 19.5 µm feature seen around AGB stars has been assigned to magnesium-iron-oxides (Posch et al. 2002), and in red giants features at 13 and 17 µm are possibly to be due to spinels (Fabian et al. 2001). Trend analysis in a large number of ISO spectra shows that the observed features are always found at the same wavelengths and are relatively narrow (Sloan et al. 2003), they do not show the large variety of peak positions observed in the outflow of the Red Rectangle. It turns out that (Mg,Fe)O provides a good identification for the features, especially longwards of 17 µm. A variation in Fe-content explains
the shift in peak position. In the left panel of Fig. 2, it is clear from interpolation that the strong 17.5 µm feature observed in one of the nodes of Position A can be explained with a material slightly more Mg-rich than Mg$_{0.6}$Fe$_{0.4}$O. In the right hand panel, sub slit extractions in position B show that the Fe-content of the (Mg,Fe)O causes the resonance to shift in peak position. The broad feature between 13–16 µm remains unidentified, but seems to correlate with the longer wavelength (18–20 µm) feature in peak position shift (Fig. 2), and could therefore perhaps be explained by oxide-rich composite grains. Other components could include spinel or silicates, which could cause a shift to shorter wavelengths for the pure oxide feature.

4. Discussion and conclusion

The rich variety of features longwards of 13 µm seen in the outflow of the Red Rectangle is possibly carried by simple oxides, and composite grains containing those oxides. The presence of such oxygen-rich species in the carbon-rich outflow is rather surprising. Explanations may include that these oxides are relics from an earlier mass loss phase, when the outflow was still oxygen-rich. Alternatively the presence of these oxides may be caused by erosion from the oxygen-rich circumbinary disk. The variations in the composition of the oxides with position in the outflow is rather unusual, given that virtually all sources showing resonances which have previously been identified with magnesium-iron-oxides or spinel, do not show any variation in peak position from source to source, or within sources (Sloan et al. 2003). It is not trivial to connect these resonances to the ones currently observed in the Red Rectangle. Further observations of the outflow in the low resolution mode of IRS are required to gain further insights in the distribution and the carriers of the broad MIR bands.

Acknowledgments. We wish to thank Mike Jura, Lou Allamandola and Xander Tielens for inspiring discussions. Support for this work was provided by NASA through the Spitzer Fellowship Program, under award 011 808-001.

References

Cohen, M., Anderson, C. M., Cowley, A., et al. 1975, ApJ, 196, 179
Cohen, M., Van Winckel, H., Bond, H. E., & Gull, T. R. 2004, AJ, 127, 2362
Fabian, D., Posch, T., Mutschke, H., Kerschbaum, F., & Dorschner, J. 2001, A&A, 373, 1125
Higdon, S. J. U., Devost, D., Higdon, J. L., et al. 2004, PASP, 116, 975
Hony, S., Van Kerckhoven, C., Peeters, E., et al. 2001, A&A, 370, 1030
Men’shchikov, A. B., Schertl, D., Tuthill, P. G., Weigelt, G., & Yungelson, L. R. 2002, A&A, 393, 867
Miyata, T., Kataza, H., Okamoto, Y. K., et al. 2004, A&A, 415, 179
Posch, T., Kerschbaum, F., Mutschke, H., Dorschner, J., & Jäger, C. 2002, A&A, 393, L7
Sloan, G. C., Kraemer, K. E., Goebel, J. H., & Price, S. D. 2003, ApJ, 594, 483
Van Kerckhoven, C., Hony, S., Peeters, E., et al. 2000, A&A, 357, 1013
Van Winckel, H. 2003, ARA&A, 41, 391
Van Winckel, H., Cohen, M., & Gull, T. R. 2002, A&A, 390, 147
Waters, L. B. F. M., Waelkens, C., van Winckel, H., et al. 1998, Nat, 391, 868