An oxygen-rich debris disk in the Red Rectangle: planet formation in an old binary?[1]

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The Red Rectangle[1] is the prototype of a class of carbon-rich nebulae surrounding evolved, low mass stars that have shed almost their entire envelope by means of a strong, dusty stellar wind as a red giant. The central star of the nebula, HD 44179, is in a rapid phase of evolution to higher temperatures, and will evolve into a white dwarf. It is member of a wide binary system[2] which is surrounded by a thick dusty disk[3,4], that formed during the red giant phase. Here we report the discovery of prominent solid state emission bands from *oxygen-rich* crystalline silicates and of CO_2 absorption at 4.27 and 15 μm. We present evidence that this O-rich material is in the circum-binary disk, while the C-rich dust is mainly in the extended nebula. The properties of

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the oxygen-rich circumbinary disk in the Red Rectangle are similar to those found in the debris disks surrounding young stars[5], which are believed to be the site of planet formation. We suggest that grain processing, and perhaps planet formation may also occur in the circum-binary disk of the evolved star HD 44179.

The Red Rectangle nebula[1] (hereafter RR) was discovered by Cohen and co-workers in 1975 as a peculiar X-shaped nebulosity. High resolution optical and near-IR imaging reveals the presence of an optically thick disk in the centre of the X-shaped nebula, with scattering lobes extending above and below the disk[3,4]. The infrared spectrum of the nebula is dominated by emission from the well-known unidentified infrared (UIR) bands[6] at 3.29, 6.2, 7.7, 8.6 and 11.3 μm, usually attributed to Polycyclic Aromatic Hydrocarbons[7] (PAHs), and proving the rich C-based chemistry of the nebula. Infrared imaging of the UIR bands shows that the carriers of these bands are located in the nebula and not in the central part (disk)[8,9]. The primary of the binary system HD 44179 has an effective temperature of 7500 K, and has a photosphere which is depleted of refractory elements but has solar C, N, O, S and Zn abundances[10]. This depletion pattern is similar to that of the gas component of the Interstellar Medium (ISM) and is the result of fractionation onto dust, and subsequent re-accretion of gas devoid of metals onto the star[11,12].

The origin of the nebula is related to mass loss and/or mass transfer in a low mass close binary system, of which the more massive component evolved to the Asymptotic Giant Branch (AGB). The system is too small to accomodate an AGB star, and mass transfer must have taken place, rapidly circularising the orbit[10,4]. The present-day eccentricity probably resulted from tidal interaction with the massive circum-binary disk, similar to that seen in young binary systems[13].

We observed the RR and its central binary on October 18th, 1997 with the Short Wavelength Spectrometer[14] (SWS) of the Infrared Space Observatory[15] (ISO). The spectrum covers the entire SWS wavelength range from 2.38 to 45.2 μm. We show the full spectrum in Fig. 1, and we show the 15 μm, and 4.5 μm (continuum subtracted) region in Fig. 2. The λ 2.4-15 μm spectrum is characterized by a rising continuum with superimposed very strong emission from the UIR bands, originating from the X-shaped nebula[8,9] (Fig. 3). We report the discovery of two new bands in the 13-15 μm region of the RR spectrum (Fig. 1) at λ 13.57 and 14.23 μm. This region contains the spectral signatures of PAH-edge structures. The new bands may be identified with PAHs containing four (λ 13.57 μm) and five (λ 14.23 μm) adjacent H atoms. A band near 13.58 μm is seen in NGC 7027, and near 13.48 μm in IRAS21282+5050[16]. These bands may be related to the band at 13.57 μm seen in the RR. A more detailed description of the PAH spectrum will be presented elsewhere. Here we concentrate on the presence of *oxygen-rich* dust and gas components.

The spectrum longward of 15 μm is dominated by numerous narrow emission bands which can be identified with crystalline silicates[17,5]. Peaks from olivines[18] ($(Mg_xFe_{1-x})_2SiO_4$) are found at 19.56, 23.75, 27.78, 29.48, and 33.85 μm, and from pyroxenes[19] ($Mg_xFe_{1-x}SiO_3$) at 33.0, 36.22, 40.56 and possibly at 43.99 μm. The last feature may also contain a contribution from crystalline H_2O ice[20]. The spectra show a remarkable degree of fine-structure in the bands (see Fig. 1), not seen previously, suggesting that several carriers contribute to the bands. The band strength ratio of the 23.75 and 33.85 μm can be used to derive the temperature of the carriers of these bands, and we find $\sim$120 K. We have fitted a simple dust model to the spectrum and find approximate values for the inner and outer radii of the O-rich dust component of 500 and 2000 AU respectively (using a distance of 330 pc), and a dust mass of 4 10^{-5} $M_\odot$, of which 13 percent is crystalline. The dust mass of the C-rich component is a factor of 10 smaller. The model severely underestimates the millimeter continuum measurements[21], and another component, with large grains, must be present. The millimeter data yield a dust mass of 6 10^{-4} $M_\odot$ [21]. This is probably a lower limit due to the presence of very large grains[22]. We find a radial density gradient for the oxygen-rich dust component of $n(r) \propto r^{-1.0}$; this value is poorly constrained however. Nevertheless it suggests that the material is not in an outflow.

At 4.27 and 15 μm, we find weak absorption from gas-phase CO_2 (Fig. 2). The 4.27 μm band may also have a contribution from solid CO_2. Given the large circumstellar extinction towards the central star, the CO_2 absorption must be of circumstellar origin. We also find *emission* from the gas-phase ^{12}CO and ^{13}CO fundamental ro-vibrational bands (Fig. 2), for which an excitation temperature of about 300-400 K is found. The excitation temperature and emission character suggest that the CO responsible for the emission at 4.6 μm is located in the nebula.

The presence of O-rich material in the RR, already suggested on the basis of OH absorption at UV wavelengths[23], is now convincingly demonstrated by our detection of CO_2 absorption and crystalline silicate emission. The OH and CO_2 absorption show that the O-rich material is in the absorbing material towards the central star. It therefore is reasonable to assume that the O-rich material is located in the circum-binary disk. The lack of the C-rich UIR emission in the central part of the nebula[8,9] (see Fig. 3), points to a *spatially separated chemistry*, dominated by O-rich material in the (outer parts of the) circum-binary disk and C-rich material in the nebula. There may be a C-rich chemistry in the *inner disk*.

We propose an evolutionary scenario in which the disk is the result of extensive mass transfer and/or mass loss while the central star was still O-rich. The high mass loss exposed C-rich interior layers, and the now C-rich outflow was forced to a strongly bipolar geometry by the presence of the massive circum-binary disk. Such a scenario can explain the C-rich nature of the extended nebula, the O-rich nature of the (outer parts of the) circum-binary disk and the pronounced X-shape of the nebula. The RR may be related to the class of C-rich AGB stars with O-rich dust shells[24]. The O-rich dust near these stars is a remnant of a previous mass loss episode when the carbon star was still O-rich. The geometry of the O-rich dust shell in these stars is not clear. It may be in a detached, expanding shell[24] or in a disk surrounding an unseen companion[25] or surrounding the entire system. The mixed chemistry of the RR nebula suggests that a binary scenario for C-stars with O-rich dust shells is plausible. This implies that such binaries may evolve into systems similar to the RR.

The strength of the crystalline bands is large compared to that seen in mass-losing AGB stars, but comparable to that seen in some planetary nebulae[17] and in young stars surrounded by proto-planetary systems[5]. The grains in the circum-binary disk are significantly larger than typical in AGB outflows or the ISM[22,26], and the weak CO rotational line emission[27] suggests that CO is depleted from the circumstellar environment. The radius of the disk derived from the ISO spectrum corresponds to keplerian velocities of the order of 1 km/s, which is in good agreement with the width of the CO rotational line emission peak[27]. This velocity is much smaller than usually found in the outflows of AGB winds (≈ 10 km/s), suggesting that the CO gas, and also the dust, are in a stationary circum-binary disk. The grain size distribution, the degree of crystallisation, the disk dimensions, the radial density distribution of the grains as well as the CO kinematics and depletion are reminiscent of the properties of gas and dust in disks surrounding young pre-main-sequence stars[28,5]. The physical processes that take place in such disks (grain coagulation, crystallisation and growth, and – potentially – planet formation) may therefore also occur in the disk of HD 44179.

The question arises whether the RR may in fact be a young object, as was suggested at its discovery[1]. A convincing argument for the evolved nature of the RR follows from its membership in a small group of low-gravity objects with similar, extreme depletion of refractory elements in the photosphere[2], all of which are binaries with orbital periods of about 1 year. The high galactic latitude of the other members of this group strongly argues for an evolved, low mass nature of the RR system. Planet *formation* so far has not been documented in the post-main-sequence phase of low mass stars. Nevertheless, since planet formation seems possible in such hostile environments as found near millisecond pulsars[29], it could well be that planet formation is now occurring in the stationary circum-binary disk of the evolved system HD 44179.

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Figure Captions

Figure 1. Full SWS grating scan (AOT01 speed 4) of the Red Rectangle nebula and its central star. The SWS apertures (14x20, 14x27, and 20x33 arcsec) cover most of the nebulosity. Data reduction was standard and done with version 6 of the Interactive Analysis system. The data of all 12 detectors per AOT sub-band were sigma-clipped, averaged and rebinned to a uniform resolution of $\lambda/\Delta\lambda = 1000$. The AOT sub-bands were then joined to form a single spectrum covering λ 2.38 to 45.2 μm.The thick tickmarks indicate the positions of the strongest oxygen-rich bands. The lower solid line gives the emissivity of olivines with T = 120 K. Note also the presence of strong emission from the unidentified infrared bands (UIRs) at $\lambda < 15$ μm (indicated by the thin tickmarks), usually attributed to Polycyclic Aromatic Hydrocarbons (PAHs). The presence of both C-rich and O-rich chemistry is related to the mass loss history of the central binary system.

Figure 2. Top: SWS spectrum in the 4.5 μm region, showing weak absorption from CO_2, emission from gas-phase ^{12}CO and ^{13}CO, and the 5.3 μm PAH feature. Bottom: SWS spectrum in the 15 μm region with weak 15 μm gas-phase CO_2 absorption.

Figure 3. Top: false-colour images of the broad-band 10 μm emission (left) and continuum subtracted narrow-band 11.3 μm emission (right) in the Red Rectangle nebula. The images were taken on Febr. 24, 1994 with the 10 μm camera TIMMI attached to the 3.6 μm telescope of the European Southern Observatory (ESO), La Silla, Chile. The pixel size is 0.33 arcsec. The broad-band 10 μm image shows that the bulk of the emission at that wavelength originates from the circum-binary disk, while the brightness distribution of the narrow-band 11.3 μm image shows that the C-rich carriers of the UIR bands are located in the extended nebula[8,9]. Bottom: ISO-SWS spectrum of the Red Rectangle. The boxes relate the C-rich component to the extended nebula, and the O-rich component to the circum-binary disk in the centre of the nebula respectively.