We present a complete study of the H$_2$ infrared emission, including the pure rotational lines, of the proto Planetary Nebulae CRL 618 with the ISO SWS. A large number of lines are detected. The analysis of our observations shows: (i) an OTP ratio very different from the classical value of 3, probably around 1.76-1.87; (ii) a stratification of the emitting region, and more precisely different regions of emission, plausibly located in the lobes, in an intermediate zone, and close to the torus; (iii) different excitation mechanisms, collisions and fluorescence.

1. Introduction

CRL 618 is one of the few clear examples of an AGB star in the transition phase to the Planetary Nebula stage: a Proto Planetary Nebula (PPN). It has a compact HII region created by a hot central C-rich star, and is observed as a bipolar nebula at optical, radio and infrared wavelengths. The expansion velocity of the envelope is around 20 km s$^{-1}$, but CO observations show the presence of a high-velocity outflow with velocities up to 300 km s$^{-1}$ (Cernicharo et al. 1989). High-velocity emission in H$_2$ is also detected (Burton & Geballe 1986). The high velocity wind and the UV photons from the star perturb the circumstellar envelope producing shocks and photodissociation regions (PDRs) which modify the physical and chemical conditions of the gas (Cernicharo et al.1989, and Neri et al.1992). Clumpiness within the visible lobes and low-velocity shocks being the remnant of the AGB circumstellar envelope are also proposed by Latter et al.(1992). H$_2$ excitation mechanisms can be investigated through our IR observations. We also propose to study the possible variations of the OTP ratio from the classical value of 3. More details are given in Herpin et al.(2000).

2. Observations

Many H$_2$ lines were detected (see Fig. 1) with these ISO Short-Wavelength Spectrometer (SWS, de Graauw et al.1996) observations: 0-0 S(J=0-15), 1-0 Q(J=1-7), 2-1 Q(J=1-7,9,10,13,14,15), 3-2 Q(J=1,3,4,5,7), 4-3 Q(J=2,3,4,7,9,10), and 1-0 O(J=2-7). The fluxes were obtained assuming the source punctual relative to the SWS beam. A SWS spectral resolution of $\lambda/\Delta \lambda = 2000$ was taken.

3. Data analysis

3.1. Location of the emission

Because of the large number of data and thus the large energy covering, we based our global data analysis on the 0 − 0 S transitions. Moreover, 0-0S(0) to 0-0S(6) emissions are not very sensitive to the extinction and thus are very reliable. A brief look on the plot of the column densities (derived from the line intensities) versus the energies of the upper levels for the uncorrected data (no absorption correction, and OTP ratio of 3 (Fig 2, left) shows first that an OTP ratio ($\chi$) of 3 seems inappropriate as the ortho-to-para ratio of the emitting region is probably different from the classical value of 3. However, a correction of the OTP ratio to around 1.76-1.87 can be seen as the column densities are systematically underestimated when the OTP ratio is not taken into account.
the same value of the OTP ratio seems not possible. Thus we introduced different values for different parts of the plot, i.e., different energies, and thus probably different regions of excitation in the PPN environment: \( \chi = 1., 1.76 \) and 1.87. But some discontinuities are still present. This is not an effect of variations in \( T_{\text{ex}} \) because in this case slopes would vary. This can only be explained by different regions of emission, and consequently can be corrected by different absorptions. We thus applied 4 different corrections of the absorption: \( A = 3.5, 10, 15 \) and 20 mag (Latter et al.1992, Thronson 1981). The result is given in the Fig. 2 (right captions).

This study of the resolution of the observed lines (see Fig. 1) shows three different parts of emission. First of all, the 0−0 S(0) to S(6) lines are totally resolved (with a SWS resolution of 200 km s\(^{-1}\)). A broad line, thus resolved, means that the emission arises from a quite large velocity region, this velocity field being then sufficiently important to broaden the line. This suggests that this part of the \( \text{H}_2 \) emission may arise from the lobes, where the velocity is larger. An intermediate zone of excitation, between lobes and torus, appears for the 0−0 S(7), S(8) and S(9) emissions, whose half power line widths are around 200 km s\(^{-1}\) (third zone on the plot) on the limit of resolution. Finally, all the other lines have small widths (50-160 km s\(^{-1}\)), and then probably arise from a low-velocity region, certainly the edge of the torus. A similar study is done for the emissions involving excited vibrational levels. The 1−0 Q lines are unresolved. We think that these emissions stem from the same intermediate zone as are the 0−0 S(7)-S(9) emissions. Moreover the “intermediate” slope derived from the column densities is another indication. The same conclusion applies for the 1−0 O lines, even if their origin is not exactly the same: this emission is probably closer to the lobes, as the derived temperature (cf. Fig. 2) is similar as what is found for the 0−0 S emission in this area. All the lines involving vibrational levels with \( v \geq 2 \) are completely unresolved and thus arise from a region close to the torus.

### 3.2. Excitation mechanisms

We attempted to fit the data with a very simple model based on a Boltzman distribution of the populations (cf. Fig. 2). For the 0−0 S emissions, the fitted temperature...
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Figure 2. Plot of the column densities (in cm$^{-2}$) versus the energies of the upper levels for uncorrected data (OTP ratio=3, left captions) and corrected data (right captions). Black and white symbols are respectively for para and ortho transitions.

Tutures and column densities are in agreement with the hypothesis of low-energy emission from shocks in the lobes (low temperatures, and high column densities, corresponding to $n(H_2) \simeq 10^6 - 10^7$ cm$^{-3}$), and high-energy emissions coming from the torus with higher temperature and weaker density. For the transitions from excited vibrational levels, we admitted that $0-0$ S(J), $1-0$ Q(J+2) and O(J+4) emissions are produced in the same region, and have the same extinction and OTP ratio. The same argument was used for the other excited vibrational emissions. We obtained different fits with slow slopes (temperatures are larger) for different $\Delta v$ emissions, which may suggest fluorescent emission.

Concerning the $1-0$ emissions, we compared our intensities to theoretical results of Sternberg (1989) and Black (1987). Moreover the temperatures are moderate, as the ro-vibrational column densities. This suggests the thermal contribution in the excitation. A clumpy structure, or one which partly shields the emitting region from the stellar UV flux may explain a low level of fluorescent emission. In thermal sources these rotational and vibrational temperatures are similar, while fluorescent sources are characterized by a much higher vibrational temperature and a much lower rotational temperature (Tanaka et al.1989). That is why emissions $1-0$ O and Q are probably more or less of thermal nature ($T_{rot} \simeq 2000-5000$ K and $T_{vib} \simeq 1000$ K for $v = 1$), but a component of fluorescent emission is probably also present. The situation seems more complicated for the other vibrational excited transitions. The only case in Sternberg (1989) and also in Black (1987) with all these emissions is the radiative fluorescent model. This strongly suggests that the emissions involving $v \geq 2$ levels are fluorescent. We resume on Fig.3 what we deduced about the excitation of the $H_2$ lines.

3.3. The OTP ratio

We attempt to explain the low OTP ratio by different mechanisms. Shocks breaking molecules and photodissociation, ionization from the central star can produce H, H+, H$_2$, H$_2^+$... who will react with H$_2$ and alter the OTP ratio. On the other hand, in a...
shocked region, the shock velocity may be important in the OTP conversion process. We think that there is in fact no OTP ratio gradient in our data, but large uncertainties, and consequently that the OTP ratio is around 1.76-1.87, the first value of 1 remaining without explanation. We thus think that the OTP ratio is fixed near the central star where low-velocity shocks occur and where atoms and ions can spoil this ratio. Part of this material is swept out into the lobes with this low OTP ratio.

4. Conclusion

Shocks in the lobes produce the low-energy 0-0 S emission, while shocks and perhaps fluorescence induce emission in a transition area. The high-energy emission may be produced by fluorescence in the torus. A mix of fluorescence and collisions may be on the origin of the 1-0 O and Q lines, while all the other emissions are dominated by fluorescence. Concerning the low OTP ratio, probably around 1.76-1.87, we think that it is fixed near the central star, the material being after swept out into the lobes, with a very non-classical value.

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