CO EMISSION FROM SHOCK AND PDR IN C-RICH PN AND POST-AGB OBJECTS

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ABSTRACT

The LWS full grating scans of the PN, NGC 7027, and post-AGB objects, GL618 and GL2688 reveal a forest of lines which are identified as CO rotational lines. These lines are used as diagnostics for warm gas around these objects.

For NGC 7027 and GL 618, the hot central star is the source of the ionizing photons, creating a PDR. GL2688 is a cooler post-AGB star with evidence of a fast wind which results in shock heated gas. From the CO observations, we can estimate the density of the molecular layer. In agreement with earlier work, we found that the molecular layer is warm (T$\sim$ 350-600 K) and dense (n$\sim$ 10^7 cm^{-3}). This may have implications on mass loss during the last stage of the evolution before stars evolve off the AGB.

Key words: Proto- and Planetary Nebulae.

1. INTRODUCTION

Just before a star evolves off the Asymptotic Giant Branch (AGB), it is thought to experience a phase of sudden increase in its mass loss rate, called a superwind. The star develops a fast wind which sweeps up the mass loss during the earlier AGB ($v_{\rm AGB}$ $\sim$ 15 km s^{-1}) as the central star becomes hotter and finally ionizes the material around it, resulting in a planetary nebula (PN).

Observations of high rotational CO lines from the Kuiper Airborne Observatory (Justtanont et al. 1997) indicate that these lines originate in a warm dense molecular layer around the star since their theoretical calculation of a spherical, constant mass loss rate cannot explain the line fluxes observed. Preliminary results of the ISO LWS (Kessler et al. 1996, Clegg et al. 1996) for NGC 7027 (Liu et al. 1996) and GL 2688 (Cox et al. 1996) confirmed the existence of such a layer. Therefore, alternative explanations of how these high CO lines are excited are needed. Two possible mechanisms are briefly discussed below.

2. SOURCE SELECTION

We obtained the LWS full grating scans as part of the guaranteed time program (PI. M.J. Barlow) of three C-rich objects in different evolutionary stages :

- GL 2688 – a post-AGB object with a cool central star (spectral type F5Iae)
- GL 618 – a post-AGB object with a hot central star (spectral type B0)
- NGC 7027 – a young PN with one of the hottest central stars known (T$\sim$ 1.5×10^5K)

The continuum subtracted spectra of these stars are shown in Fig. 1, along with a Gaussian fit to each CO line detected. A variety of atomic lines are also present e.g., [OI] 63 μm, [CII]158 μm.

3. HEATING MECHANISMS

For the case of a PN, FUV radiation from the central star is the main source of heating the gas. FUV photons can also dissociate molecules and ionize atoms, forming a photodissociation region (PDR e.g., Tielens & Hollenbach 1985).

Also, since it is known that during the post-AGB phase a fast wind can develop, the gas can also be heated by shock waves (e.g., McKee & Hollenbach 1980) resulting from this fast wind as it ploughs into the superwind which was lost during the AGB phase.

For both mechanisms, the radiative cooling is via atomic fine structure lines (e.g., [OI] and [CII]) and molecular rotational lines, in our particular case, CO rotational lines.

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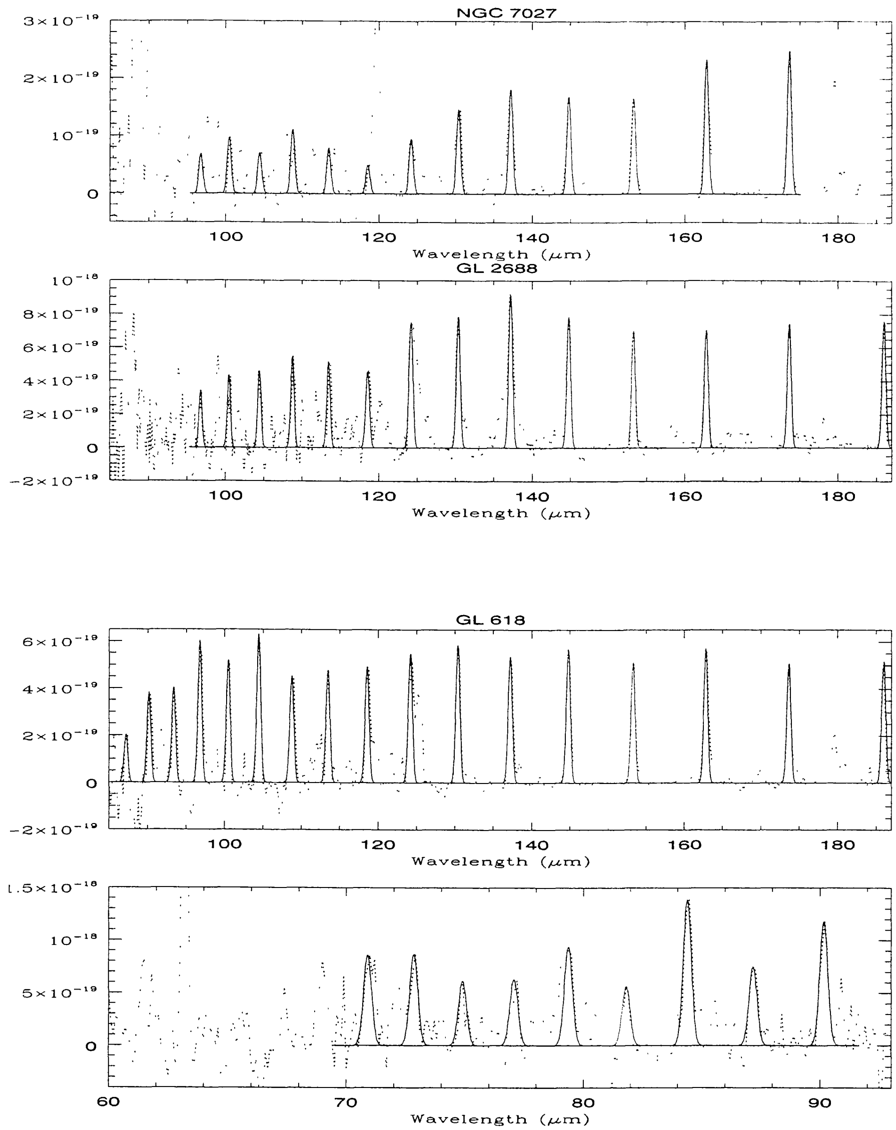

Figure 1. Continuum subtracted spectra of NGC 7027, GL618 and GL 2688 (dotted line) with Gaussian fits of all CO lines detected (solid line). The flux is in W cm^{-2} μm^{-1}.

4. NGC 7027

There is abundant evidence for importance of FUV photons for heating of the warm molecular gas observed towards NGC 7027 and we will concentrate our modelling effort for this source on PDRs.

From CO line fluxes we deduce, from a least-squares rotation diagram fit, a temperature for the molecular layer of 350 K (Fig. 2), suggesting that the bulk of the radiation comes from a high density layer far away from the central star – the radius of the HII region is $\sim$ 4 arcsec while the low J CO has an inner radius of 10 arcsec (Graham et al. 1993). We adopt the former size to derive Ω (table 1), localizing the high J CO in the zone very near to the ionization front ($\Delta A_v \leq 1$ mag) as expected for a dense PDR. The main cooling lines are [OI] 63 and 146 μm and [CII] 158 μm (Liu et al. 1996, Justtanont et al. 1997). Our PDR models (Table 1) with the C/O=0.6 and 3.0 are shown in Fig. 3 with the former tracing the observed line fluxes for J$\geq$17. Liu et al.'s (1996) calculation of optically thin emission from a 1000 K gas produces a good fit for J$\leq$23. The discrepancy between the temperatures derived from the rotation diagram and optically thin calculation may be due to the LTE assumption in the former. From these results, a combination of excitation temperature and density can give reasonably good fit to the data but in the PDR model, high density is required to get the CO gas close enough to the surface that it is warm enough. There is a large discrepancy between the previously observed KAO and LWS flux for J=17-16 reported here.

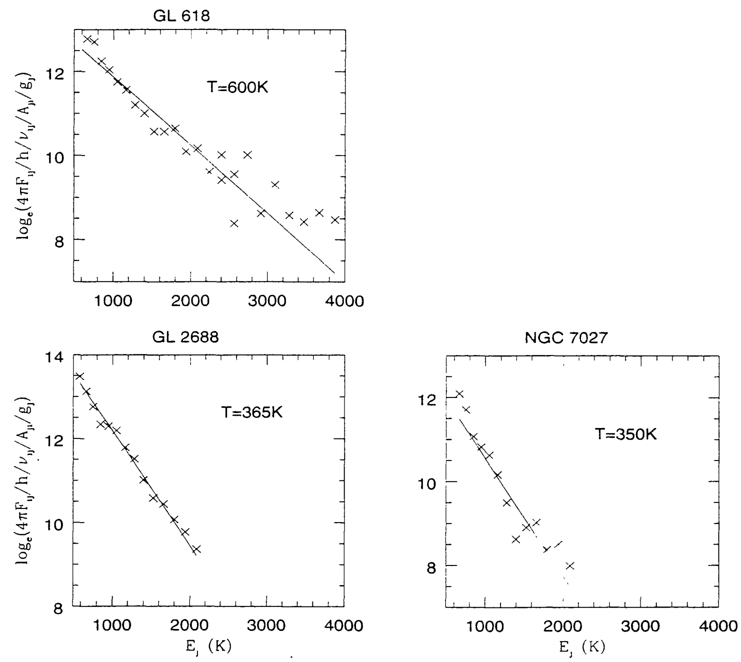

Figure 2. Rotation diagrams of all three objects. A straight line indicates the least-squares fit to the data.

Table 1. Parameters for PDR and shock models

	NGC 7027 (PDR)	GL 2688 (shock)	GL 618 (PDR)
n (cm^{-3})	1.0E+7	1.0E+7	1.0E+7
G_0 (Habing)	6.0E+5	1.0E+8	3.0E+7
T_{eff} (K)	3.0E+4[a]	6.0E+3	3.0E+4
v_s (km s^{-1})	-	30.	-
Ω (sr)	4.2E-10	6.0E-10	2.0E-10

[a]lower temperature than observed due to model limitation

5. GL 2688

The CO and HCN mm-line observations of this object show a presence of a broad wing, attributed to a fast wind from the central star (Young et al. 1992). Sahai et al. (1998) observed the star using HST/NICMOS, revealing multiple mass loss shells from the last stage of its AGB lifetime. We estimate a source size, Ω, of 6×10^{-10} sr (=5 arcsec), indicated by the size of the H_2 emission (Sahai et al. 1998). This object shows very strong CO rotational lines from J=14-13 up to J=27-26. The best fit to the rotation diagram gives a temperature of 365K, cf 400 K by Cox et al. (1996). There are significant differences between some line fluxes measured with the KAO compared to the LWS line fluxes. Some CO lines suffer from blending effect (J=18-19 to J=21-20, Fig. 1).

Our 30 km s^{-1} J-shock model predicts that the peak CO line flux should occur at J=22, longwards of the observation (Fig. 3). This implies that either the shock velocity is lower than in our model and may be a non-dissociated J-shock, or that the preshock density is lower. The latter requires a larger beam filling factor than the HST observation of 5 arcsec to fit the CO line fluxes observed. Our shock model underestimates fluxes from lower transitions (after multiply by a factor of two to account for CO abundance in C-rich object), which may be due to the presence of another cool layer. Note that we detect neither the [OI] nor the [CII] lines (Cox et al. 1996). The latter is not expected to make a strong cooling contribution in shock models, however, we expected to see the [OI] lines. Their absence could be due to the fact that atomic oxygen quickly combines with free atomic carbon to form CO in this cool dense layer, or CO is not dissociated due to low shock velocity.

6. GL 618

This object is more evolved than GL 2688 and is on its way to becoming a very young planetary nebula. Its nebulosity is partially ionized in the optical but no PAH emission is seen in the IR. The flux ratio of the [OI]63 μm and [CII]158 μm lines ($\sim$ 10) supports the idea that the dominant heating in this source is due to the FUV photons, i.e., a PDR.

The best fit to the rotation diagram suggests a temperature for the molecular layer of 600 K – a warmer layer (i.e., closer to the central star) than the previous two objects, which agrees with the fact that we see higher rotational lines of CO up to J=37-36 tran-

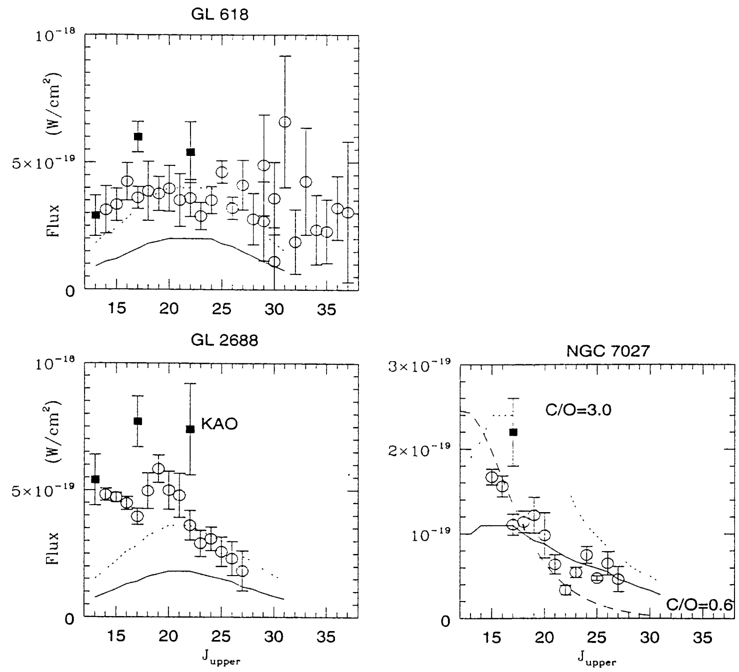

Figure 3. Model fits to the observed line fluxes. For GL 2688 and GL 618, dotted lines are our model (solid line) multiplied by a factor of two to account for an increase in the C/O ratio. Dashed line in NGC 7027 plot is an optically thin model by Liu et al. (1996).

sition, although the lines are increasingly noisy at these high transitions. The J=29-28 and 30-29 lines are detected in both SW and LW detectors. Again, we multiplied our predicted line fluxes by a factor of two since our model assumes a C/O=0.6 (Fig. 3). From the H_2 image taken by Latter et al. (1995), the estimated size of the PDR is 2×10^{-10} sr ($\sim$ 3 arcsec).

7. SUMMARY

The LWS grating observations of the CO lines from all these objects can be explained by heating due to either a PDR (for NGC7027 and GL 618) or shocks (GL2688). The temperatures derived for this molecular layer by fitting the rotation diagrams are of the order of 300-600 K. Our PDR/shock models require a density of $\sim 10^7$ cm^{-3} in order to explain the line fluxes observed. For NGC7027 and GL618, the main cooling lines are due to atomic fine structure lines of [OI] and [CII]. Neither line is detected in GL2688, probably due either to a fast recombination of O and C to form CO in the warm layer or a low velocity shock.

In the future, we will take into account the carbon chemistry in the PDR calculation which is more appropriate for C-rich objects in this report.

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