ATOMIC FINE-STRUCTURE LINES FROM PROTOPLANETARY NEBULAE

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ABSTRACT

We have observed atomic fine-structure lines in the far-infrared (FIR) from protoplanetary nebulae (PPNe). The sample is composed of 24 objects, also including for comparison a few planetary nebulae and AGB stars. Data on O I, C II, N II, Si I, Si II, S I, Fe I, and Fe II lines were obtained. PPNe are found to emit in these low-excitation atomic transitions only when the central star is hotter than $\sim$ 10,000 K. This result suggests that such lines predominantly arise from photodissociation regions (PDRs), and not from shocked regions. The line widths determined from our Fabry-Perot data also suggest that the FIR lines arise from relatively quiescent PDR gas as opposed to shocked gas. Our results are in reasonable agreement with predictions from PDR emission models, allowing the estimation of the density of the emitting layers from comparison with the model parameters. The C II line intensity has been used to measure the mass of the low-excitation atomic component in PPNe, since this transition has been found to be a useful model-independent probe to estimate the total mass of these PDRs.

Key words: ISO – Atomic data – Stars: AGB and post-AGB – (Stars:) circumstellar matter – Stars: mass-loss

1. INTRODUCTION

In the late phases of the life of solar-type stars, a fast evolution from the AGB to planetary nebulae (PNe) takes place. In less than 1000 years, these stars evolve from a large and cool red giant, with a molecule-rich envelope, to a tiny and very hot blue dwarf surrounded by a mostly ionized atom-rich nebula. Post-AGB stars or protoplanetary nebulae (PPNe) constitute the intermediate evolutionary stage and often show intermediate properties.

PPNe are expected to contain some atomic neutral gas in photodissociation regions (PDRs) and/or shocks. Between the transition from molecular gas to ionized gas, the inner nebula can become a PDR, where molecules are photodissociated but atoms are still mostly neutral. The atomic gas in a PDR is heated primarily through the photo-ejected electron from dust grains. On the other hand, PPNe are characterized by strong shocks, often axially distributed. These shocks probably take place between the old AGB wind, which is slow and isotropic, and the post-AGB wind, likely very fast and bipolar. In principle, such shocks can also dissociate molecules, and so the low-excitation atomic emission could also come from shocked regions that are being rapidly cooling down.

Before ISO was launched, it was almost impossible to study these cool atomic regions, because they mainly emit in the FIR. Fine-structure transitions are known to be the most important coolants in PDRs (see Tielens & Hollenbach 1985), the heating being due to far-ultraviolet photons or shocks. Those lines are excited collisionaly at a range of temperatures of $\sim 10^2$–10^3 K.

In this paper, we will compare all our data for O-rich objects with models. In forth-coming papers, Castro-Carrizo et al. (2000) and Fong et al. (2000), a detailed comparison of both O-rich and C-rich models with the data of the respective sources will be presented.

2. OBSERVATIONS AND DATA ANALYSIS

We have observed a sample of 24 evolved objects, mostly PPNe but also including a few PNe and AGB stars for comparison. The observed O-rich sources are: OH 26.5+0.6, Mira, Betelgeuse, R Sct, AFGL 2343, HD 161796, 89 Her, M 1-92, M 2-9, Hb 12, Mz-3, and NGC 6302. The C-rich sources are: IRC +10216, IRAS 15194–5115, LP And, IRAS 22272+5435, AC Her, SAO 163075, AFGL 2688, Red Rectangle, IRAS 21282+5050, AFGL 618, NGC 6720, and NGC 7027. Also we observed off-source points to determine the contribution from galactic cloud emission.

Our purpose was to detect the atomic fine-structure lines: [O I] (63.2 μm, 145.5 μm), [C II] (157.7 μm), [N II] (121.9 μm), [Si I] (68.5 μm, 129.7 μm), [Si II] (34.8 μm), [S I] (25.2 μm), [Fe I] (24.0 μm, 34.7 μm) and [Fe II] (26.0 μm, 35.3 μm). For that we used both ISO spectrometers, LWS (43-196.7 μm) and SWS (2.4-45 μm), with different optical elements, grating and Fabry-Perot (FP).

Only the LWS-FP and SWS-FP allowed us to obtain enough spectral resolution to get some information about the kinematic behavior of the emitting gas. The typical rms obtained with the LWS/SWS grating is $\sim$ 0.1-1/1-10

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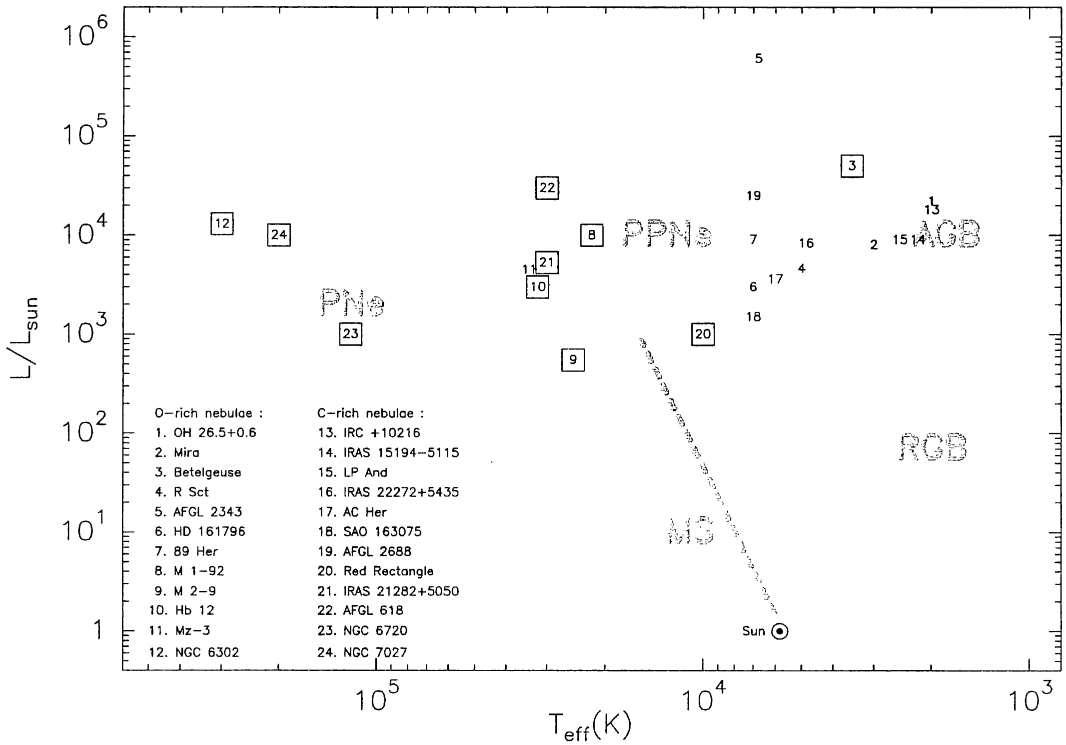

Figure 1. Distribution in the H-R diagram of the observed sources. Squares around a number indicates that the source is detected in atomic line emission.

10^{-12} erg cm^{-2}s$^{-1}\mu$m^{-1}. The peak intensity of the most intense detected lines is $\sim 10^{-8}$ erg cm^{-2}s$^{-1}\mu$m^{-1} for PNe, and $\sim 10^{-9}$-10^{-10} erg cm^{-2}s$^{-1}\mu$m^{-1} for PPNe.

In Figure 1 we show the sources in an H-R diagram. The detected sources, in any of the mentioned transitions, are marked in that figure. See Castro-Carrizo et al. (2000) and Fong et al. (2000) to get a detailed description of the observations and of the obtained results.

We fitted the few FP lines that we detected, with a flat-top parabolic line profile convolved with the instrumental line profile. Although the results are not conclusive, we derived expansion velocities for the emitting gas that are, in general, comparable to those observed in CO which arises from the quiescently expanding circumstellar envelope. Thus, this suggests that the atomic line emission arises from PDRs instead of shocked regions.

3. INTERPRETATION OF THE OBSERVATIONS

3.1. Dependence on the stellar parameters

By direct comparison of the observational results with the stellar temperature, that are shown in the H-R diagram (Figure 1), we find that only nebulae surrounding stars with effective surface temperature $\gtrsim$ 10,000 K are detected. The only exception is Betelgeuse, in which the intense far-infrared lines are known to be a consequence of the UV emission by its active chromosphere (see Rodgers & Glassgold 1992). The Red Rectangle, that has a stellar temperature $\sim$ 10,000 K and has been detected in atomic lines, also shows a well known UV excess. On the other hand, the observation of the only non-detected source with $>$ 10,000 K, Mz 3, is strongly contaminated by galactic emission, and so the non-detection is not very significant. It is, for instance, striking that AFGL 618 and AFGL 2688 show different atomic FIR emission, because although they have different stellar temperatures, their envelopes are very similar at other respects. It is also noticeable the lack of emission in AFGL 2343, in spite of that has a very massive molecular envelope.

The strong dependence of the low-excitation atomic gas emission on the temperature of the central star argues clearly in favor of that the emitting regions are mainly PDRs in our sources. Therefore, shocks or interstellar radiation do not seem to be in the origin of this molecular dissociation. This suggests that the PDRs may develop unavoidably in this brief intermediate evolutionary phase for most solar-type stars. Our observations show the first clear evidence of PDRs in PPNe, originated by photon emission coming from the central stars; usually PDRs appear in interstellar clouds associated to hot stars.

3.2. Comparison with PDR line emission models

To compare with the PDR models (according to Tielens & Hollenbach 1985, Spaans et al. 1994 and van den Ancker 1999), we calculate the incident far-ultraviolet radiation in the PDR:

$$G = \frac{LF_{\mathrm{UV}}}{4\pi R_i^2 G_0} \qquad (1)$$

where L is the luminosity of the source, F_{UV} is the efficiency of the star's output in the ultraviolet (UV), R_i is the inner radius of the PDR, and G_0 is a unit of average interstellar radiation field flux in the UV range. See the above papers to have a detailed description of the parameters. Note that G is distance independent, since both L and R_i vary as D^2.

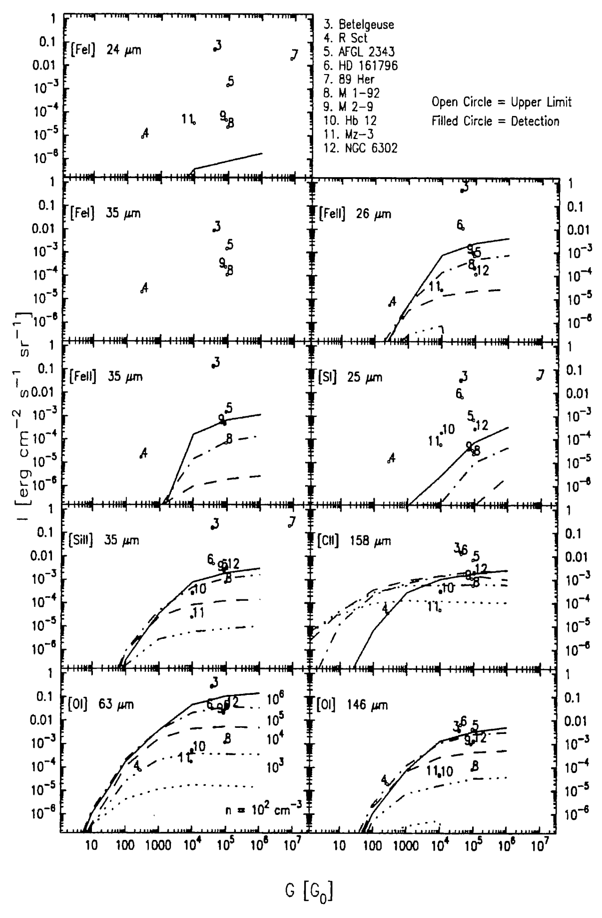

Figure 2. Comparison of the observations of O-rich sources with the corresponding PDR model.

In principle the PDR model calculates the emission I from a plane-parallel layer, so that, to compare with predictions we calculate $I = F_{obs}/(4\pi\theta_i^2)$ where F_{obs} is the observed intensity, and θ_i is the inner angular radius of the PDR. Comparison of the data with the model predictions for O-rich sources, from van den Ancker (1999), is plotted in Figure 2. Such a comparison is quite satisfactory. The densities required to explain the data are quite compatible for the different lines except for Si II, perhaps because the Si abundance is too low in the model.

The main disagreement between observations and these predictions is that the PDR models do not account for the strong contrast found between the atomic emission of nebulae around stars with more or less than $\sim$ 10,000 K. In some of the cooler PDRs, the model gives much smaller densities than the expected values. The reason could be that the model assumes chemical and physical equilibrium during all the post-AGB evolution. But the cooler nebula (whose lives are $\lesssim$ 200-300 yr) have not had enough time to photodissociate CO (whose characteristic time is usually longer, Spaans et al. 1994). This characteristic dissociation time determines when the PDR mass starts to develop in the nebula. After such a critical time, the dissociation equilibrium starts to hold. See, for example, the case of AFGL 2688, that we know is as massive as AFGL 618 but cooler, and for which we have not got any detection. Moreover, in these cool stars, there are too few photons with sufficient energy (>11 eV) to photodissociate the CO and H_2, and the photodissociation regions are very small even if there was sufficient time to create a PDR (Spaans et al. 1994).

So far we have only compared our data with the oxygen-rich model, but we are working on a carbon-rich one.

3.3. Comparison with shock models

Theoretical shock model predictions are adapted from van den Ancker (1999), for both J- and C-type shocks. The comparison between the predictions of those models and our observations is less satisfactory than it was with the PDR theory. From such a comparison we can relate the intensity of the emission with the velocity of the shocks. So, from the J shocks model predictions, we note that the C II observation could suggest much higher shock velocities that those deduced from the Si II and Fe intensities. From comparison with the C shocks model, the velocities suggested by O I and S I lines are very different. Moreover the C-type shocks can not explain the intense C II emission.

On the other hand, from the deconvolved Fabry-Perot detections we have obtained moderate velocities that are comparable to those found at half power in CO lines.

In summary, the low-excitation atomic emission in PPNe does not seem to come from shocks.

3.4. Calculation of the low-excitation atomic mass

The best tracer of the low-excitation atomic regions is probably the C II emission, because CO is dissociated and C I is ionized almost at the same time. Under the next two approximations, the C II line intensity becomes practically independent of the density and temperature, depending only on the total emitting mass (assuming that the C abundance is known). The first condition is that $T_{ex} \gg 91.2$ K, where 91.2 K is the [C II] transition energy. This allows assuming that level population is independent of the excitation temperature T_{ex}. This approximation also implies that collisional excitation is important enough to neglect the stimulated radiative one. The second assumption is that the emission is optically thin. We have checked, from the low fluxes measured and the relatively high temperatures expected in PDRs, that this condition is fulfilled in all the relevant cases.

The mass of the low-excitation atomic gas becomes

$$M(\mathrm{gr}) = 4.15\ 10^{43}\ F_{obs}(158\mu\mathrm{m})\ D(\mathrm{kpc})^2 \quad , \qquad (2)$$

where F_{obs} (erg cm^{-2}s^{-1}) is the flux detected on the earth, and D is the distance to the source. When the approximation $T_{ex} \gg 91.2$ K is not fulfilled at all, we have to take into account a correction factor F_c (≥ 1), that must be included in Equation 2. F_c is only noticeably > 1 for very low densities (n$\lesssim 10^3$ cm^{-3}), and densities can be estimated from the comparison with the PDR models.

Table 1. The sources in the first group are oxygen-rich, and carbon-rich in the second one. The correction factors F_c for the carbon-rich sources have been estimated from the densities obtained from comparison with the oxygen-rich model.

Source	10^{32} M(g)/F_c	F_c	$M(M_\odot)$
R Sct	< 0.03	1	$< 10^{-3}$
AFGL 2343	< 40	1	< 2
HD 161796	< 1	1	< 0.05
M 1-92	< 4	1	< 0.2
M 2-9	< 0.5	1	< 0.03
Hb 12	7*	1.5	0.6*
Mz 3	< 5	1	< 0.3
NGC 6302	50	1	3
IRAS 22272+5435	< 5	1	< 0.2
AC Her	< 0.2	1	$< 8\ 10^{-3}$
AFGL 2688	< 2	1	< 0.08
Red Rectangle	< 0.02	1	$< 8\ 10^{-4}$
IRAS 21282+5050	30	1	2
AFGL 618	1*	1	0.06*
NGC 6720	3	1.5	0.2
NGC 7027	20	1	0.9

In Table 1 we show the derived low-excitation atomic mass for the sources where [C II] emission was observed, and upper limits in the cases where there were no detections. In the table the nebulae are ordered according by increasing stellar T_{eff}. An asterisk means that we have not observed off-source points. In cases where we only know an upper limit, we have taken F_c =1. F_c is calculated from the densities estimated by comparison with oxygen-rich PDR models, even for carbon-rich objects. Note also that, due to the large extent of NGC 6720, only one part ($\sim 1/3$) of this source could be observed by ISO.

4. CONCLUSIONS

We have observed atomic fine-structure lines in the far-infrared from protoplanetary nebulae.

Only nebulae that surround stars with $T_{eff} \gtrsim 10{,}000$ K have been detected. This seems to imply that low-excitation atomic emission comes from PDRs.

The comparison with PDR line emission models is quite satisfactory. The main disagreement comes from the contrast of the emission from stars that are hotter and cooler that 10,000 K, that the models predict to be less strong than observed values. The origin of this seems to be the relatively long characteristic time of the CO dissociation compared to the evolution time of the star from the AGB.

The emission predicted by models of shocked regions cannot reproduce the observed line intensities consistently for all lines. Moreover, the Fabry-Perot detections indicate smaller velocities than expected in shocked regions.

We can calculate the total mass of the low-excitation atomic gas, only from the detected [C II] flux and the distance to the source. The reliable masses obtained for the PNe and some PPNe are very high, $\sim 1\ M_\odot$, in some cases.

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