Herschel/HIFI: first science highlights

LETTER TO THE EDITOR

Herschel/HIFI observations of high-*J* CO transitions in the protoplanetary nebula CRL 618[*]

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ABSTRACT

Aims. We aim to study the physical conditions, particularly the excitation state, of the intermediate-temperature gas components in the protoplanetary nebula CRL 618. These components are particularly important for understanding the evolution of the nebula.
Methods. We performed *Herschel*/HIFI observations of several CO lines in the far-infrared/sub-mm in the protoplanetary nebula CRL 618. The high spectral resolution provided by HIFI allows measurement of the line profiles. Since the dynamics and structure of the nebula is well known from mm-wave interferometric maps, it is possible to identify the contributions of the different nebular components (fast bipolar outflows, double shells, compact slow shell) to the line profiles. The observation of these relatively high-energy transitions allows an accurate study of the excitation conditions in these components, particularly in the warm ones, which cannot be properly studied from the low-energy lines.
Results. The ^{12}CO $J = 16-15$, $10-9$, and $6-5$ lines are easily detected in this source. Both ^{13}CO $J = 10-9$ and $6-5$ are also detected. Wide profiles showing spectacular line wings have been found, particularly in ^{12}CO $J = 16-15$. Other lines observed simultaneously with CO are also shown. Our analysis of the CO high-*J* transitions, when compared with the existing models, confirms the very low expansion velocity of the central, dense component, which probably indicates that the shells ejected during the last AGB phases were driven by radiation pressure under a regime of maximum transfer of momentum. No contribution of the diffuse halo found from mm-wave data is identified in our spectra, because of its low temperature. We find that the fast bipolar outflow is quite hot, much hotter than previously estimated; for instance, gas flowing at 100 km s^{-1} must have a temperature higher than ~200 K. Probably, this very fast outflow, with a kinematic age <100 yr, has been accelerated by a shock and has not yet cooled down. The double empty shell found from mm-wave mapping must also be relatively hot, in agreement with the previous estimate.

Key words. stars: AGB and post-AGB – circumstellar matter – stars: mass-loss – planetary nebulae: general – planetary nebulae: individual: CRL 618

1. Introduction

Protoplanetary nebulae (PPNe) are known to present very fast bipolar outflows, along with slower components, which are probably the remnants of the mass ejection during the previous AGB phase. The bipolar flows typically reach velocities of 100 km s^{-1}, and affect a sizable fraction of the nebular mass, ~0.1–0.3 $M_\odot$ (Bujarrabal et al. 2001). These dense flows actually represent intermediate states in the spectacular evolution from the spherical and slowly expanding circumstellar envelopes around AGB stars to the planetary nebulae, which usually show bipolar or ring-like symmetries. Such remarkable dynamics is probably the result of the interaction between the AGB and post-AGB winds: axial, very fast post-AGB jets colliding with the denser material driven isotropically away from the star during its AGB phase (e.g. Balick & Frank 2002). The presently observed bipolar outflows would then correspond to a part of the relatively dense shells ejected during the last AGB phase, mostly their polar regions, accelerated by the shocks that propagate during the PPN phase.

The massive bipolar outflows in PPNe, as well as the unaltered remnants of the AGB shells, usually show strong emission in molecular lines (Bujarrabal et al. 2001). PPNe have been accurately observed in mm-wave lines, particularly by means of interferometric maps with resolutions ~1″. Thanks to those observations, the structure, dynamics, and physical conditions in these nebulae are often quite well known. However, observations of the low-*J* transitions are not very useful for studying the warm gas components. The well-studied $J = 2-1$ and $J = 1-0$ transitions of ^{12}CO only require temperatures of T_k ~15 K to be excited. Indeed their maximum emissivity occurs for excitation temperatures of 10–20 K, and the line intensities and line intensity ratios only slightly depend on the excitation state in relatively warm gas. Needless to say, observations in the visible or near infrared ranges tend to select hot regions, with typical temperatures over 1000 K. The proper study of warm regions, 100 K $\lesssim T_k \lesssim$ 1000 K, therefore requires observations at intermediate wavelengths, in the far infrared (FIR) and sub-mm ranges.

Because of the role of shocks in PPN evolution, these warm regions are particularly important for understanding nebular structure and evolution. In some well-studied cases, e.g. M 1–92 and M 2–56 (Alcolea et al. 2007, Bujarrabal et al. 1998, Castro-Carrizo et al. 2002), the high-velocity, massive outflows are

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Fig. 1. HIFI observations containing detected ^{12}CO and ^{13}CO lines in CRL 618 (T_{mb} vs. rest frequencies). Frequency scales and detected lines are indicated; note that the observations are performed in DSB mode.

Table 1. Summary of the *Herschel* telescope characteristics.

Line	Band	DSB T_{sys}	HPBW	T_{mb}/T_a	Cal. uncert.
6–5	2	130 K	31″	1.4	10%
^{13}CO 10–9	4	400 K	20″	1.4	20%
^{12}CO 10–9	5	800 K	20″	1.4	15%
16–15	7	1300 K	12″	1.5	30%

2. Observations

We used the *Herschel*/HIFI instrument (Pilbratt et al. 2010; de Graauw et al. 2010) to observe the $J = 6-5$, $10-9$, and $16-15$ transitions of ^{12}CO and ^{13}CO in the PPN CRL 618 (^{13}CO $J = 16-15$ was not detected); see Figs. 1 and 2. Other molecular lines were also detected within the observed frequency ranges. The data were taken using the two orthogonal HIFI receivers available at each band. Both receivers work in double side-band (DSB) mode, which effectively doubles the instantaneous IF coverage. Care was taken when choosing the local oscillator frequency, maximizing the number of observed interesting lines.

The observations were obtained in the dual-beam-switching (DBS) mode. In this mode, the HIFI internal steering mirror chops between the source position and an emission-free position 3′ away. The telescope then alternatively locates the source in either of the chopped beams, providing a double-difference calibration scheme, which allows a more efficient cancellation of the residual standing waves in the spectra (see additional details in Roelfsema et al. 2010). This procedure works very well except for the $J = 16-15$ lines, where strong ripples were found in some spectra, especially in the V-receiver.

The HIFI data shown here were taken using the wide-band spectrometer (WBS), an acousto-optical spectrometer that provides simultaneous coverage of the full instantaneous IF band in the two available orthogonal receivers, with a spectral resolution of 1.1 MHz. The data shown in all the figures have been resampled and smoothed to a resolution of about $2\,km\,s^{-1}$.

The data were processed with the standard HIFI pipeline using HIPE, with a modified version of the level 2 algorithm that yields unaveraged spectra with all spectrometer sub-bands stitched together. Later on, the spectra were exported to CLASS using the hiClass tool within HIPE, for further inspection, flagging out data with outstanding ripple residuals, final averaging, and baseline removal. We checked that the profile of the ^{12}CO $J = 16-15$ line, in particular, is not significantly affected by ripples, which in fact are not noticeable even in the relatively flat parts of the final spectrum. The data were originally calibrated in antenna temperature units and later converted into main-beam temperatures (T_{mb}). In all cases we assumed a side-band gain ratio of one. A summary of the telescope characteristics and observational uncertainties is given in Table 1.

We also report here ^{12}CO $J = 4-3$ and $7-6$ lines observed from the ground with the APEX telescope. These observations were performed in preparation for the HIFI observations in 2006 and more details will be given in a future paper. We used the FLASH receiver equipped with two FTS spectrometers, which allows simultaneous observation of the two CO lines; see Heyminck et al. (2006) for a description of the system. The resulting APEX spectra are shown in Fig. 2, after being rescaled to T_{mb} units using the values for the telescope efficiencies given by Güsten et al. (2006). In this figure, we also show IRAM 30 m data data for ^{12}CO $J = 1-0$ and $2-1$ from Bujarrabal et al. (2001).

found to be very cold, with temperatures $\lesssim 20$ K, which implies very fast cooling in the shock-accelerated gas. No warm component representing the gas recently accelerated by the shock front has been identified in these sources. In other cases such as CRL 618, interferometric imaging of the ^{12}CO $J = 2-1$ line shows that dense gas in axial structures presents higher temperatures (Sánchez Contreras et al. 2004, hereafter, SC04). But, precisely because of their relatively high excitation, the temperature estimate in these components from CO $J = 2-1$ is very uncertain. Indeed, even the presence of such high excitation in the dense bipolar outflows in CRL 618 remained to be demonstrated.

Other attempts to study the warm gas in CRL 618 were carried out by (i) Justtanont et al. (2000) from ISO data with low spectral resolution; (ii) Pardo et al. (2004), who focused on the chemistry of the different components; and (iii) Nakashima et al. (2007), who also obtained maps of the $J = 6-5$ transition in CRL 618, but with less detail than in SC04.

The *Herschel* Space Telescope is well-suited to studying warm gas around evolved stars in the FIR and sub-mm. The high spectral resolution that can be achieved with its heterodyne instrument HIFI (better than $1\,km\,s^{-1}$) is particularly useful for this purpose, since kinematics offers a fundamental key to understanding this warm, shocked gas. Here we present *Herschel*/HIFI observations of CRL 618 in several molecular lines of ^{12}CO and ^{13}CO that were obtained as part of the guaranteed-time key program HIFISTARS, which is devoted to the study of intermediate-excitation molecular lines in nebulae around evolved stars.

Fig. 2. ^{12}CO lines observed in CRL 618 with HIFI, in units of $T_{\rm mb}$ vs. LSR velocity. Other CO lines observed from the ground are also shown. Note that the high-velocity wings of the ^{12}CO $J = 10-9$ profile are affected by emission of other lines (Fig. 1).

3. Nebula model

Detailed mapping of CO emission at 1mm wavelength was performed by SC04, who derived the physical conditions, structure, and dynamics of the nebula from model fitting of their maps. Several warm components were identified (see Fig. 3): a compact dense core with temperatures ~100 K (decreasing with distance to the center), a double (empty) shell with a typical temperature of 200 K, and a very fast bipolar outflow (running inside the cavities) with temperatures ≲100 K (also decreasing with distance). Another cooler component was found: a diffuser halo expanding at 17 km s^{-1}. The empty shells show a roughly elliptical shape that strongly suggests that they are the result of a bow-like shock, but with a moderate expansion velocity. The expansion velocity of the compact component was found to be particularly low, ≲10 km s^{-1}.

As a starting point, we adopted a similar description of the nebula structure. Calculation of the expected emission in our case must be more sophisticated, because the high-*J* CO transitions cannot be assumed to be thermalized in the whole nebula. Therefore, we determined the CO level population performing LVG calculations for a large number of points in the model nebula. LVG calculations are fully justified here because of the high velocity gradients characteristic of this source. With these values of the populations we calculated the emissivity and absorption coefficients at each point. Finally, the brightness distribution is calculated along a number of lines of sight and is convolved with the telescope beam shape, described by a Gaussian function. The results are profiles in units of main-beam temperature, directly comparable to our observations. Therefore, opacity effects are properly taken into account, both in the excitation and line profile calculations. We have checked that the high-*J* lines are often underexcited in our case, particularly for densities under ~10^6 cm^{-3}.

More detailed discussions of the code and involved uncertainties will be presented in a forthcoming paper. Here we mostly discuss a preliminary comparison of the model results with our observations of the ^{12}CO $J = 16-15$ line. The model fitting cannot be considered as satisfactory without studying all the observed profiles, as well as the mm-wave maps, requiring a very careful treatment of the numerical uncertainties and a detailed discussion of the nebula structure.

4. Results

We present in Fig. 2 our observational results for the ^{12}CO lines obtained with HIFI, together with other lines observed from the ground (Sect. 2). The baseline of the $J = 16-15$ line is not well determined, because of the lack of spectral coverage and the presence of other lines, which mostly affects the intensity of the line wings at extreme velocities.

We have mentioned (Sect. 1) the interest of observing high-*J* transitions in order to better estimate the excitation conditions in warm regions. Our highest transitions require several hundred K to be significantly excited; for instance, the energy of the ^{12}CO $J = 16$ level is equivalent to 750 K.

We have compared our data with the predictions of the model presented in Sect. 3, originally developed to explain the mm-wave maps (see assumed nebula structure in Fig. 3). This model can reasonably explain the central part of the high-*J* emission with only moderate changes. We can see in Fig. 4 the comparison between the observations and predictions for a model in which the density and temperature of the shells have been increased by 25% (dashed, red line). The asymmetry in the observed profile cannot be explained by radiative transfer phenomena, and it probably reveals true asymmetries with respect to the equator that are not included in our models. The central spectral feature is very narrow and comes from the low-velocity compact component of the nebula; in fact, the fitting is improved if the velocity of central component is still decreased, to typical values ≲5 km s^{-1}, but keeping the strong velocity gradient characteristic of this region, in order to reproduce the triangular shape of the observed feature. The two intense humps at both sides of the central maximum would come from the hollow shells.

However, the high-velocity wings are severely underestimated by our standard model, and we would have to significantly increase the excitation conditions of the very fast bipolar outflow of CRL 618 to reproduce their intensity. We can also see in Fig. 4 our predictions for a model similar to the previous one, but with $T_{\rm k}$ ~ 200 K in the regions that present expansion velocities ~100 km s^{-1}. Other parameters of the fast outflow, particularly its velocity and density distributions do not change with respect to the original model. The asymmetry between the red and blue line wings is not reproduced by our predictions also in this case. It is remarkable that the high-velocity outflow obviously contributes to the emission at the profile central features. Therefore, in this model the requirements to reproduce the secondary maxima are significantly weaker, and a temperature similar to or even lower than assumed in our original model for the empty shells would be compatible with the observations. The general properties of the central, dense component mentioned before, in particular its low velocity, are required in this case too. The high velocity wings are also detected in emission from other molecules, such as H$_2$O, HCN, and CN (Fig. 1), which must be significantly abundant in this recently shocked gas.

The relatively high temperatures deduced here for the fast bipolar flow relax the discrepancy usually found between the

Fig. 3. Basic model properties used in our calculations, see Sects. 3 and 4 (adapted from SC04).

Fig. 4. ^{12}CO $J = 16-15$ observed line and predictions of our model (Sects. 3, 4), without (dashed, red line), and with (dot-dashed, green line) significant increase of the excitation in the very fast outflow.

high excitation of the shocked gas predicted by theoretical models and the observational results (an intricate theoretical problem not discussed in this letter, see e.g. Lee et al. 2009). However, the discrepancy persists. Lee et al. (2009) predict temperatures of the high-velocity gas in CRL 618 over ~1000 K and too weak CO emission in all rotational lines, since shocks are expected to dissociate molecules.

The low-excitation component of the nebula model by SC04, the extended halo, has apparently no counterpart in the observations, because the model predicts a very low intensity from such cool gas and the high-J line profiles do not seem to require any contribution from it.

In Fig. 1 we also show our HIFI spectra of ^{13}CO lines. The ^{13}CO $J = 16-15$ observations are not very sensitive, so the line is not detected with a limit $T_{mb} \lesssim 0.2$ K. As we can see, the contrast between ^{12}CO and ^{13}CO lines is high (mainly in the line wings, about a factor ten for the highest transitions). This result is compatible with our calculations, which suggest moderate opacities in high-J ^{12}CO lines from the main nebular components, in particular with $\tau(16-15) \lesssim 1$ for gas flowing at $\gtrsim 100$ km s^{-1}.

Our results can therefore be summarized as follows:

1. We detected high-J CO emission using *Herschel*/HIFI. The high-velocity line wings characteristic of this source become progressively dominant as the level energies increase, with ^{12}CO $J = 16-15$ showing a spectacular composite profile.

2. The temperature of the very fast bipolar outflow in CRL 618 is high, significantly higher than the previously adopted values. SC04 proposed a temperature for this component <100 K, which, in view of the intense line wings seen in the $J = 16-15$ transition, must be significantly increased. From our calculations, we estimate that gas flowing at about 100 km s^{-1} must have a temperature ~200 K. We suggest that this very fast outflow, with a kinematic age <100 yr, was accelerated by a shock and has not yet fully cooled down. The rest of the physical conditions are not significantly changed, therefore the dynamical parameters (including the high momentum and kinetic energy) remain the same as those deduced by SC04.

3. We confirm the low expansion velocity of the very dense, central component. This low velocity coincides with a significant increase in the mass-loss rates during the last ~400 yr of the AGB phase (SC04). We suggest that the significant decrease in the expansion velocity is caused by the ejection of material by the star during the last AGB phases being driven by radiation pressure under a regime of maximum momentum transfer from radiation to gas.

We recall that our analysis is preliminary. Further developments, in particular including fitting the mm-wave maps and our HIFI data, are required.

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