WAITING FOR FIRST: THE EVOLUTION OF MOLECULAR OUTFLOWS

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Abstract

We review some aspects of our research activity, based on ground-based mm-wavelengths and ISO observations, which have been addressed in the effort to investigate the evolution of the molecular outflows associated with star forming regions. The approach given by the study of the shock chemistry has been used, observing emission due to molecular species as e.g. SiO, H_2O, OH, H_2S, SO, SO_2. The results suggest criteria based on line profiles and abundance ratios which allow to get the evolutionary stage of the young stellar objects driving the mass loss process, and call for the study of emission due to high excitation transitions of Si-, O- and S-bearing molecules which occurs at the FIRST frequencies. The high spectral resolution given by HIFI as well as the PACS and SPIRE capability to obtain imaging spectroscopy of quite extended star forming regions represent an unique opportunity to investigate the high temperature chemistry, tracing the high excitation conditions associated with the region closely linked with the shock front.

Key words: ISM: clouds – ISM: jets and outflows – ISM: molecules – Radio lines: ISM

1. Introduction

The star forming process occurs in molecular clouds by the gravitational collapse of dense gas. Outflow motions are closely coupled with infall: both happen simultaneously and are linked since the very first evolutionary stages of the star forming regions. The protostar winds interact with the surrounding material, giving rise to molecular outflows. In this scenario, outflows play a major role, providing a mechanism for angular momentum loss to allow the assembling of the protostar, stopping gravitational collapse and probably fixing the central object mass. Moreover, outflows contribute to the disruption of the star forming dense core (e.g. Lada 1985, Richer et al. 2000, Bachiller & Tafalla 2000 and references therein).

Despite the enormous progress done during more than twenty years of investigations, some basic questions about molecular outflows still remain unanswered. For instance, it is not still understood how outflows evolve with time and how the observed properties depend on the outflow evolutionary stage. Outflows are associated with all the stages of the star forming process and are linked with the youngest stellar objects known to date, the Class 0 protostars. Thus, it is worth noting that to investigate the outflow time evolution gives the opportunity to investigate the earliest stages of the star forming process, and allows to try to focus the research on the onset of the star forming process, which is one of the challenge of modern astronomy.

The main problem for the study of the outflow evolution is the identification of an internal clock which allow to get an age estimation. A possible approach is given by the study of the shock chemistry. Protostellar outflows are supersonic and then give rise to shocks which compress and heat the surrounding gas, leading to temperatures which can exceed 2000 K. At such high temperatures the energy barriers between neutral molecules can be overcome, and the chemistry of certain species is altered significantly. Moreover, shocks can drive sputtering due to dust-molecule or to dust-dust collisions which can produce the injection of species from the grain mantles to the gas phase (e.g. Schilke et al. 1997, Caselli et al. 1997). As the gas cools the chemistry is again dominated by the usual low-temperature reactions and depletion of molecules onto dust grains starts again to be important reducing the abundance of the newly formed molecular species. The molecular and atomic species associated with molecular outflows emit at far-infrared (FIR) and sub-mm wavelengths (e.g. Bachiller & Pérez Gutiérrez 1997, Nisini et al. 1999). Taking into account that the occurrence of shocks definitely alters the abundance of the molecular species and that, as a consequence, different molecules trace different physical conditions, the study of the chemistry is a precious tools to investigate the evolutionary status of the molecular outflows. With the present contribution, we stress the importance of observing emission at FIR and sub-mm wavelengths due to molecular species closely connected with shocks and molecular outflows such as e.g. SiO, H_2O, OH, H_2S, SO and SO_2.

In the next items it will be described some aspects of our present research activity, based on Infrared Space Observatory (ISO) and ground-based mm-wave observations, which will constitute the starting points of future FIRST projects.

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

2. Line profiles

A possible approach to the study of the chemical evolution is the observations of the profiles of selected transitions. This has been suggested by studies conducted at mm-wavelengths on the profiles of SiO line profiles in samples of molecular outflows (Codella et al. 1999). The SiO lines can exhibit a variety of profiles, ranging from narrow lines (1–3 km s^{-1}) at ambient velocities to broad emission (10–20 km s^{-1}), with complex shapes consisting of a blend of low and high velocity components as intermediate stages. Figure 1 shows three SiO (J = 2–1) spectra detected towards three young stellar objects (YSOs) in different evolutionary stages, from the Class 0 L1448-mm to the more evolved HH7-11 complex. These different profiles could be caused by an evolutionary effect, with the low velocity emission due to SiO molecules which, once produced at high velocities, are slowed down because their interaction with the surrounding quiescent gas. The SiO results propose the study of the spectra profile due to molecular species associated with shocks as a tool to investigate the evolution of molecular outflows. These results call for further high spectral and spatial resolution observations of species closely connected with high temperature chemistry and emitting in the FIRST spectral range, such as H_2O and H_2S. Indeed, emission tracing high excitation conditions and that could be associated with regions near the shock front would be instructive.

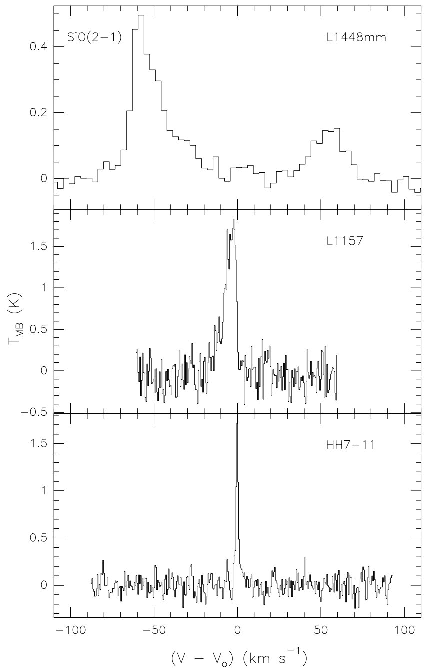

Figure 1. Silicon monoxide spectra (J = 2–1) of L1448mm (Bachiller et al. 1991), L1157 (Bachiller & Pérez Gutiérrez 1997) and HH7-11 (Codella et al. 1999). The horizontal axis is the velocity measured with respect to the ambient gas (v_o).

3. Chemical evolution

3.1. The O-bearing species

Species pertaining to the Oxygen chemistry (O, H_2O, OH and O_2) are particularly suited for the outflow investigation since their relative abundances are highly dependent on the outflow evolution (e.g. Bergin 1998). This has been also highlighted by ISO observations towards YSOs with different ages. Figure 2 shows the ISO spectra of three objects in different evolutionary stages, L1448-mm (Class 0), L1614N (Class I) and LkHα234 (Class II). It is possible to see that: (i) the strongest H_2O emission lines are associated with the Class 0 object and (ii) OH seems to be associated with an evolutionary phase later than that of water. Several reasons concur to produce this behaviour; water tends to be depleted onto grains with timescales of the order of 10^5 yr (for densities of about 10^5 cm^{-3}) and thus it is not very abundant in old outflows (Bergin 1998). Moreover, as the protostar evolves the influence of its stellar radiation field becomes greater, quickly dissociating the freshly produced water in favour of OH. High spatial resolution observations of the H_2O and OH lines which emit at IR and submillimeter wavelengths would allow to study in better details possible relationships between the evolutionary stage of the YSOs and the emission lines due to O-bearing molecules detected in their spectra.

3.2. The sulphuretted species

Other tools to investigate the outflow evolution can be provided by the study of the Sulphur chemistry. Sulphur is relative abundant (only 20 times less then Carbon) and is able to form a wide variety of compounds (e.g. CS, H_2S, SO, SO_2, OCS). However, the observations of sulphuretted molecules in the interstellar medium have always provided surprising results: for instance the spatial distribution of SO and SO_2 in molecular clouds can differ from that of most other molecules. In the past, gas-phase ion-molecule models have been unsuccessful to explain the observed abundances of S-bearing species in molecular clouds. Recent chemical models predict an enhancement of SO abundance for particular solutions, characterized, for instance, by low-ionisation and/or by a low C/O ratio (Swade 1989, Le Bourlot et al. 1995). However, Sulphur chemistry can be seriously affected by grain surface reactions. In particular, H_2S is thought to be mainly formed on grains. Shock waves injects H_2S into the gas phase leading to very fast production of SO, SO_2 and OCS (Charnley 1997, Hatchell et al. 1998). Alternatively, shock-driven chemical models (e.g. Pineau des Forêts et al. 1993) predict the enhancement of H_2S through the reactions $S + H_2 \rightarrow SH \rightarrow H_2S$. Thus, given the previous scenario, considering the relatively rapid evolution of

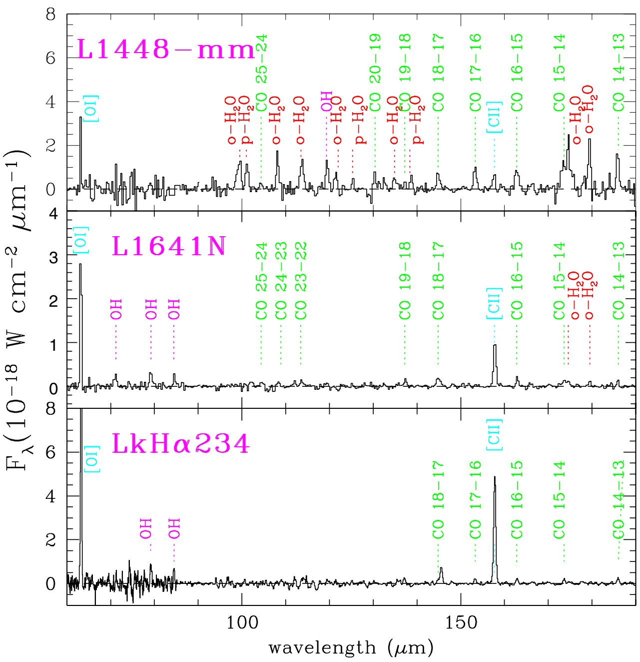

Figure 2. The low resolution, FIR spectra, obtained with ISO-LWS, of three objects in different evolutionary stages: the Class 0 L1448-mm (upper panel; Nisini et al. 1999), the Class I L1641N (middle panel) and the Class II LkHα234 (lower panel; Giannini et al. 1999).

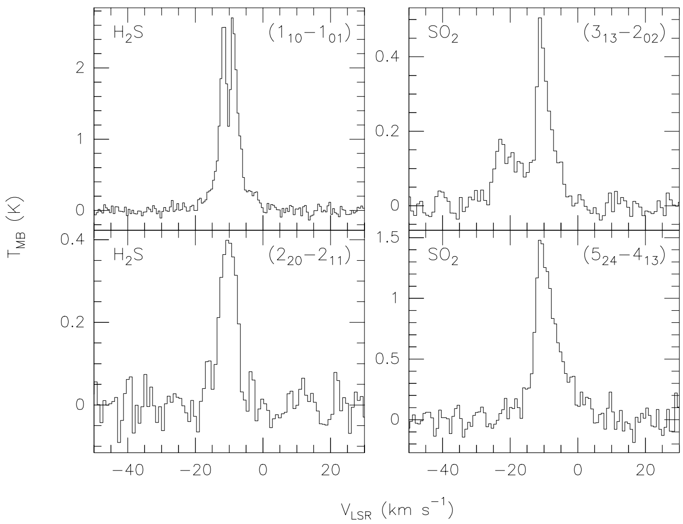

Figure 3. Examples of H_2S ($J_{K_-K_+} = 1_{01}$–0_{01} and 2_{20}–2_{11}) and SO_2 ($J_{K_-K_+} = 3_{13}$–2_{02} and 5_{24}–4_{13}) line profiles towards the CepA outflow (Codella et al. 2001).

the Sulphur chemistry in shocked regions, it is tempting to try to use as chemical clocks some abundance ratio such as e.g. SO/H_2S and SO_2/H_2S in order to study the evolutionary stage of bipolar outflows. In particular, it is reasonable to expect H_2S within the shocks, whereas SO and SO_2 could also trace post-shock regions. A first effort has been done by investigating the chemically rich CB3 outflow through a survey of S-bearing molecules at mm-wavelengths: the results (Codella & Bachiller 1999) show that such abundance ratio can successfully estimate the outflow evolutionary stage. Another example is given by the CepA outflow (Codella et al. 2001). Figure 3 reports the CepA line emission due to the H_2S ($J_{K_-K_+} = 1_{01}$–0_{01} and 2_{20}–2_{11}) and SO_2 ($J_{K_-K_+} = 3_{13}$–2_{02} and 5_{24}–4_{13}) transitions, which have an energy excitation of about 28, 84, 8 and 22 K, respectively. The four emissions are associated with different line profiles and velocity ranges, suggesting that each transition is tracing different physical conditions. These preliminary results call for further higher excitation multiline observations in order to sample the hot gas closely associated with the shocked gas.

4. Why FIRST?

FIRST will be the first space observatory to cover the submillimeter and FIR part of the electromagnetic spectrum. It will have a science payload complement consisting of three instruments and offers an unique opportunity for photometry and spectroscopy in the 60-670 μm range. The three instruments are: (i) HIFI, a heterodyne very high resolution spectrometer covering 157-625 μm, (ii) PACS, a bolometer array camera and photoconductor spectrometer covering 60-210 μm and (iii) SPIRE, a bolometer detector array camera and spectrometer covering 200-670 μm. With the present contribution, we propose to continue with the present investigations of molecular outflows through the study of emission due to very high excitation transitions of Si-, O- and S-bearing molecules which exclusively occurs at the FIRST frequencies. The investigation of the high temperature chemistry will allow to trace the regions closely linked with the shock front.

Fast low resolution spectral surveys of extended star forming regions will be performed using the PACS and SPIRE spectrometers in the spectral range 447-4997 GHz: the most promising sources will be observed at higher resolution using HIFI. In this way, FIRST will provide an unique opportunity to obtain imaging spectroscopy of star forming regions, carefully tracing their physical conditions and their chemical evolution. In particular, the chemical investigation should assign relative ages to sources in the same complex or cluster, providing a precious possibility to trace the interaction of YSOs with their surroundings and to study the triggered star forming process.

Finally, it is worth noting that PACS and SPIRE will allow to obtain continuum observations at 100, 170, 250, 350 and 500 μm. Such wavelengths are associated with the peak of the black-body emission at temperatures in the range 10-50 K, i.e. at temperatures typical of continuum emission of Class 0 (7-10 K) and Class I (20-40 K) objects. Therefore, given also the high spatial resolving power, by using FIRST continuum observations it will be possible to undoubtedly derive the spectral energy distribution of the sources driving the outflow motions. Thus, continuum observations will provide with further criteria to study the evolution of molecular outflows, which will support those given by spectroscopy.

4.1. FIRST and the line profiles

HIFI is the only instrument at wavelengths up to $\sim$ 2000 GHz with a very high spectral resolution. Moreover, HIFI will allow a deep investigation of the line profiles typical of emission coming from high temperature gas associated with outflow motions. The HIFI high sensitivity will be fundamental to detect the weak high velocity outflow wings. With HIFI it will be possible to investigate the relationship between the linewidths and the evolutionary stage of the observed shocked gas, as suggested by the few ground-based observations. The HIFI spectral range allows, at least for some molecules such as H_2O and H_2S, to observe transitions both at low (20-50 K) and high (>1000 K) excitation temperatures. In this way, the line profile criteria will be hopefully applied to relatively cool H_2O and H_2S gas components, produced in high velocity and high temperature conditions, and successively slowed down because the interaction with the ambient medium. Finally, it is worth noting that the high spectral resolution will allow also the study of other typical spectral patterns associated with the process of star formation, such as infall asymmetry and self-absorption.

4.2. FIRST and the Oxygen chemistry

FIRST for the first time will allow to trace the main species involved in the oxygen chemistry (OI, O_2, H_2O, OH) at different degree of excitation. HIFI will have in particular the sensitivity to detect different lines of O_2, for which only upper limits are so far obtained with SWAS. Moreover, it will be possible to detect both the ground level transitions of ortho- and para-H_2O and higher excitation transitions; this will allow to derive determinations of the water abundance much reliable than that estimated both with ISO and SWAS. The abundance ratios from the various species at different excitation conditions will allow to finally understand their relative role in the warm gas cooling and as Oxygen reservoirs.

Moreover, high spatial resolution observations of the H_2O, OH and CO lines which emit at IR and submillimeter wavelengths will allow to study the evolutionary stage of YSOs: the relative H_2O and OH abundances will be used to constrain the physical history of the molecular gas in star forming regions.

4.3. FIRST and the Sulphur chemistry

In addition to the more abundant species, the instruments onboard FIRST will have the sensitivity to detect less abundant molecules which are however important tracers of the outflow chemical evolution (e.g. the Si- and S-bearing molecules). FIRST will allow to investigate such molecular species through high excitation transitions. The high angular resolution provided by FIRST is essential in order to study the detailed relationship of the molecular species with the outflow structure; for instance, the bow shocks have a size of 5-20 arcsec in one of the best studied outflows such as L1157. The high spatial resolution is thus fundamental in order to investigate the expected different distributions of the shocked gas components in different evolutionary stages, trying to use abundance ratios as chemical clocks. Moreover, multiline analysis will allow to study the excitation conditions in different environments and to constrain for the physical parameters (such as temperature, abundance and density structures) of the studied regions.

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