THE STUDY OF PROTOSTELLAR OUTFLOWS WITH FIRST

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Abstract

In this contribution, we present an observing program we would like to carry out with the FIRST instrumentation, aimed to investigate the early phases of protostellar evolution through the study of the outflow phenomenon. The importance of the FIR/sub-mm investigation for the study of outflows has been demonstrated by the recent observations obtained with the Infrared Space Observatory (ISO). Here we will highligth the main results obtained with ISO showing that FIRST will be the natural step forward for this research. The main topics which can be addressed, using in particular the PACS and HIFI spectroscopic capabilities, are the study of the energetics governing the infall/outflow system, and the outflow chemical and physical evolution.

Key words: Stars: formation – ISM: jets and outflows – ISM: molecules

1. Introduction

The formation and propagation of bipolar outflows is a phenomenon inherent to the first stages of star formation, being closely associated with disk accretion and the consequent mass loss through the onset of strong collimated winds or/and stellar jets (Bachiller & Tafalla 1999). The understanding of both the details of the mechanisms producing the outflow acceleration and the way in which energy and momentum are transferred from the protostellar accretion disk to the flow, is therefore fundamental in order to get indirect information on the star formation process itself.

Molecular outflows display a large range of excitation conditions, due to the complex way in which the interaction between stellar winds/jets and ambient medium is taking place. Emission of millimeter molecular lines (usually CO) at excitation temperatures of about 10-20 K is commonly used to probe the outflow large scale morphology and dynamics. This cold emission component is however commonly associated with much higher excitation conditions, usually localized along the outflow axis, and traced by molecular hydrogen vibrational lines (at $T_{\rm ex} \sim$ 2000 K) or by optical and UV lines in Herbig-Haro objects (at $T_{\rm ex} \sim 10^4$ K). This hot gas is directly probing the shock interactions taking place along the flows (e.g. Reipurth & Raga 1999).

The far infrared (FIR) spectral range covered by the FIRST instrumentation will allow to trace gas excitation from few tens of kelvin up to more than 2000 K, which is not accessible from ground. The importance of the FIR in the study of the outflows appears clear from the inspection of Figure 1, which shows the main cooling channels in the post-shocked regions as a function of the shock parameters. Depending on whether the shock velocity is larger or smaller than the Alfvén velocity of the ions, we can have a shock strongly dissociative (J-type) or magnetically supported and non-dissociative (C-type) (see e.g. Hollenbach 1997). Independently from the shock type, for pre-shock densities larger than 10^3 cm^{-3} the cooling occurs mainly in the far infrared, either in the [OI]63μm transition and in rotational transitions of abundant molecular species, such as CO, H_2O and OH. It is therefore clear that far infrared spectroscopy becomes essential to study the outflow phenomenon in the dense environments of young protostars. This has been also demonstrated with observations obtained by the ISO-LWS spectrometer. An example is given in Figure 2, where we show the FIR spectra from the well known outflow in the L1448 dark cloud, which appear dominated by molecular emission from CO and H_2O (Nisini et al. 2000). The contribution at the gas cooling due to the warm gas traced by ISO results to be more than 90% of the total shock luminosity emitted along the flow. The analysis of the ISO-LWS spectra has however allowed to study only the averaged properties of the shocked gas, due to the large field of view (∼80″) and poor spectral resolution (∼300) of the instrument in its grating mode. The much better spatial and spectral resolution of the FIRST instrumentation, coupled with its much improved sensitivity, it will be ideal to address in depth the scientific problems highlighted by the ISO results.

2. The infall/outflow system

The physical conditions along outflows change with the driving source evolution. Outflows from Class 0 sources are highly collimated, show on average a larger ratio of kinetic over bolometric luminosity, and are often characterized by the presence of molecular jets (Bachiller & Tafalla 1999). As the protostar evolves the outflow attains a wide opening angle and its power diminishes; at the same time

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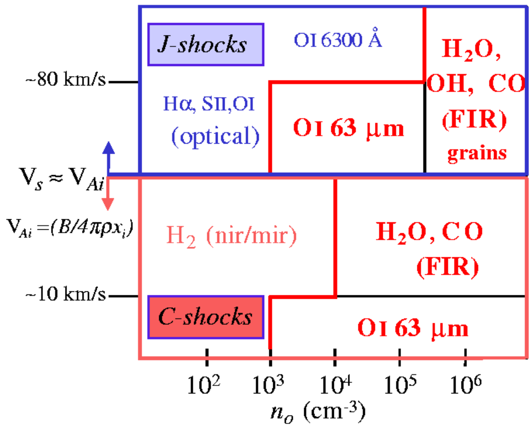

Figure 1. Main cooling channels of the post-shocked medium as a function of shock velocity and pre-shock density. The different regimes of J- and C- type shocks are obtained depending on whether the shock velocity is larger or smaller than the ions alvenic velocity. This diagram shows that for pre-shock densities exceeding 10^3 cm^{-3} the cooling is mainly achieved through gas and dust emission in the far infrared spectral range.

the jets become mostly atomic and the occurrence of HH objects increases. These modifications could be induced by changes in the outflow acceleration mechanism with evolution, coupled by a decrease of the source infall rate, and by a contemporary modification of the environment in which outflows are expanding. However, until more direct observations in the circumstellar regions close to where outflows originate will become available, especially during the Class 0 stage, no firm conclusions can be drawn. Particularly needed are observations aimed to trace the acceleration wind/jet directly emanated by the protostar, which is not clearly identified for the youngest sources.

This can be achieved by FIRST which will be able to investigate the structure and physical conditions at the base of the flow using as tracers transitions with excitation temperatures comparable to the kinetic temperature of the emitting gas (i.e. $T_{ex} > 100$ K), thus allowing to have a more correct estimation of its physical parameters (including mass loss rate and wind luminosity) than derivable by means of millimeter transitions alone, which usually trace only the swept-out gas after the shock passage. The PACS camera will in particular allows to obtain a multiline analysis of the species (mainly OI, CO, H_2O and OH) which, together with H_2, are involved in the gas radiative cooling from the outflow. The spatial resolution achieved by the camera ($\sim 10''$) is comparable to the typical size of the outflow shock emission knots and will be moreover good enough to give detailed maps of most of the nearby outflows, which usually have about $3'$-$4'$ of extent (see Figure 3). It will therefore possible to derive the temperature and density structure of the warm gas components expecially in the innermost outflow region, which, together with ground-based observations will allow a direct comparison between the different acceleration mechanisms and a reliable estimate of the total energy deposited in the flow. The comparison with different models will moreover benefit by the possibility to observe the profile of selected transitions with HIFI, and thus to obtain the velocity gradient of the warm gas along the flow. Such high-resolution observations will be also very effective in discriminating the outflowing gas from quiescent emission originating both from the cloud (for low excitation transitions) and from the YSO warm envelope.

Moreover a direct measure of the mass loss rate will be obtained by measuring with PACS the [OI]63μm transition produced by the protostar wind shock, according to the prescriptions by Hollenbach (1985). In addition, high resolution observations with HIFI of selected lines of CO and H_2O excited in the protostar infalling envelopes will allow to derive the mass accretion rates from the modelling of their inverse P-Cygni profile. In this way, it will be possible to directly measure for the first time the ratio between accretion and ejection rates, which is very dependent on the outflow acceleration mechanism and its time evolution, giving also an important measure of the efficiency of the accretion process (see e.g. Richer et al. 2000).

3. The shock chemistry

The shocks driven by outflows strongly alter the chemical composition of the medium in which the flow is travelling. Consequently, atoms and molecules can change their abundances by order of magnitudes with respect to pre-shock conditions. In Table 1 we report a list of some of the most important molecules whose abundance have been measured to drammatically change along the outflows.

Abundance variations in shocks are connected either to an high temperature chemistry not efficient in normal cloud conditions, and to the presence of dust grains, such as sputtering and grain-grain collisions, and thermal evaporation from grain mantles (e.g. Langer et al. 2000). The efficiency of all these processes depends in turn on the shock type and on the pre-shock conditions, leading to different chemical paths and consequently to specific chemical signatures. Therefore, the measurements of abundances from different species is a powerful tool to get information either on the local excitation conditions and on the outflow history (see also Codella et al., this conference).

In this contest a relevant place is given by the chemistry of the O-bearing species. This is because it involves among the most abundant species either in quiescent and

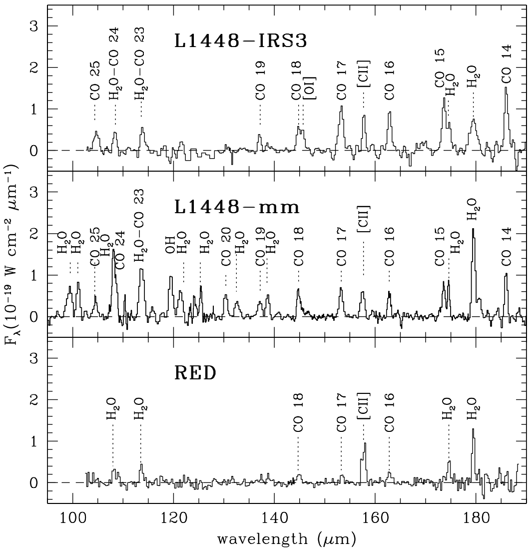

Figure 2. ISO-LWS spectra obtained in the L1448 outflow (Nisini et al. 2000). The upper and middle panels show the spectra of the two Class 0 protostars L1448-mm and L1448-IRS3, while the lower panel presents the spectrum of the mm source outflow red lobe.

Table 1. Molecular abundance variations between cold clouds and shocked outflow regions

Molecule	Cold cloud abundance	Outflow abundance	Ref.
H_2O	10^{-7}–10^{-8}	10^{-5}–10^{-4}	1,2,3
SiO	$<10^{-12}$	10^{-10}–10^{-6}	4,5
SO	$\sim10^{-9}$	$\sim10^{-7}$	6
CH_3OH	$\sim10^{-9}$	$\sim5\,10^{-7}$	6
NH_3	$\sim10^{-8}$	$\sim10^{-6}$	7
HCN	$\sim10^{-8}$	$\sim10^{-7}$	6

References: 1. Snell et al. 2000, 2. Giannini et al. 2000, 3. Saraceno et al. 1999, 4. Codella et al. 1999, 5. Martin-Píntado et al. 1992, 6. Bachiller & Perez-Gutierrez 1997, 7. Tafalla & Bachiller 1995

in the outflow processed gas, and because it is a very active chemistry, strongly dependent on both temperature and time evolution, thus providing an extremely efficient diagnostic mean. On the other hand, most of the species involved (O, H_2O, OH and O_2) are observable only from space in the FIR/submm spectral range and therefore only with ISO it has been possible to investigate for the first time the oxygen chemistry in outflow shocked regions in a more systematic way. High water abundances have been in particular observed by ISO only in flows for very young Class 0 protostars (Giannini et al., 2000, Nisini 2000), showing that water can be a powerful age indicator. A de-

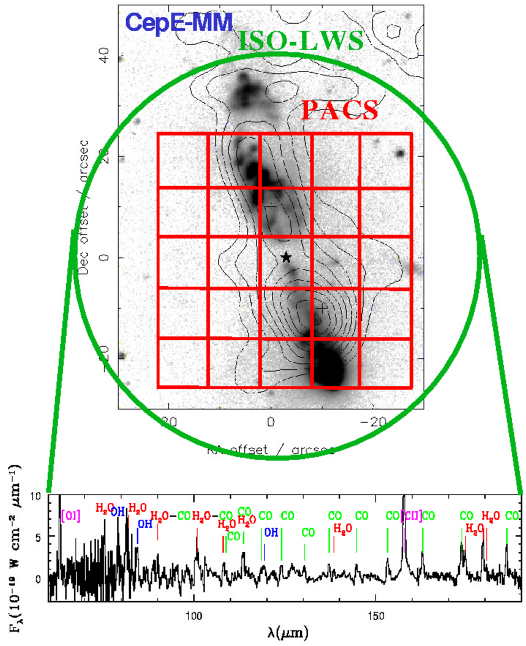

Figure 3. CO map and H_2 emission (Hatchell et al. 1999) of the outflow driven by CepE-MM source (at a distance of 730 pc), with superimposed the focal plane spatial sampling of ISO-LWS (green circle) and PACS (red grid), respectively. The averaged LWS spectrum of the region is shown at the bottom of the figure (Giannini et al. 2000).

tailed comparison of the measured abundances and physical conditions with chemical models for the water formation and evolution are however hampered by the ISO low spatial resolution, which does not allow to obtain abundances estimates over the relevant spatial scales, and to the impossibility of measuring reliable abundance ratios of different species, due to the difficulty of separating, either spatially or spectroscopically, different emission components. As an example, one of the results find by the analysis of the water content in Class 0 sources, is that there is a trend for the water abundance to increase with the gas temperatures up to T_{gas} of about 1000 K where a value of about $5\,10^{-4}$ is reached (see Giannini et al., this conference). This is a somehow unexpected result since theoretically all the oxygen should be converted into water once a gas temperature of about 300 K is reached (Kaufman & Neufeld 1996). To better understand the origin of this behaviour it will be extremely useful to study the H_2O/O abundance ratio in different flow positions as a function of the gas temperature. However, being the OI very easily excited by different mechanisms likely to be simultaneously present inside the large LWS beam (like C- and J-type shocks, and photo-dissociation), this can be efficently done only by mapping this ratio over the outflow region at the relevant spatial resolution.

FIRST for the first time will allow to trace the main species involved in the oxygen chemistry 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 (Goldsmith et al., 2000). Moreover, with HIFI it will be possible to detect both the ground level transitions of ortho- and para-H_2O ($T_{ex} < 50$ K) and higher excitation transitions (up to more than 1000 K); this fact, together with the possibility to discriminate different emission components by means of the line profiles, will allow to derive determinations of different abundance ratios much reliable than those estimated with ISO. We stress the importance of tracing, possibly with the same instrument, all the relevant species involved in chemical reactions, in order to have a much better diagnostic capability both for the physical conditions and for the abundance measurements, which can be used to infer variation of the excitation conditions both along the outflow and with the source evolution.

4. FIRST observing strategy

Although a defined observing strategy is now premature, we can however provide a breakdown for a possible observing program with order of magnitude estimates of the observing time needed given the expected instrumental sensitivities.

The aim of the proposal is to investigate about 20 protostellar sources and their associated outflows. The sources will be selected to be low-mass protostars (to have simple systems and minimize confusion with other strong excitation mechanisms relative to HII and photo-dissociation regions) of Class 0/I (for which the FIR cooling is expected to largely dominate over the NIR and optical lines). At the present stage we foresee to perform the following PACS and HIFI observations:

1. a PACS full spectral scan at the central position, covering both the exciting source and the region at the base of the outflow. All the 20 sources can be imaged in 30 hrs at a limiting flux of about $5\,10^{-21}$ W cm^{-2} (5σ), i.e. about 10 times better than ISO-LWS.
2. PACS mapping of the entire flows in about 10 lines selected among H_2O, O, OH and CO transitions at different excitation energies in order to obtain maps of both abundance ratios and excitation. If we consider a flow extent of about 4 arcmin (typical of nearby outflows, e.g. L1448), this can be achieved with 4 PACS pointings (excluding the central position). A limiting 5σ flux of about 10^{-21} W cm^{-2} ($\sim$50 times better than ISO-LWS) is achieved in about 4 min per lines.
3. HIFI observations of the same lines selected for the PACS mapping, in 10 positions along the outflow axis, in order to have dynamical information of the excited gas. At a limiting flux of $\sim 3\,10^{-21}$ W cm^{-2}, this part of the program will require about 300 hrs.

Our program should in total require about 400 hrs of FIRST observing time.

5. Conclusions

We have presented a possible observing program to be performed with the instrumentation on-board FIRST, aimed to the study of the protostellar outflows by means of far infrared spectroscopy. The main topics which can be addressed by this program are the understanding of the energetics governing the infall/outflow system, and the study of the outflow chemical and physical evolution. In addition, since outflows are suitable laboratories for the shock chemistry, the proposed observations can be also efficiently used to study the chemical recycling of the ISM induced by the star formation process.

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