SPECTROSCOPY OF STELLAR JETS, OUTFLOWS, AND YOUNG STELLAR OBJECTS WITH THE INFRARED SPACE OBSERVATORY

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ABSTRACT

The Infrared Space Observatory (ISO) was an extremely successful European space mission that gave us an unparallel view of the Universe in the infrared, and provided us with hundreds of observations of star forming regions and bipolar outflows. Three of the instrument teams, in charge of the infrared camera (CAM) and the two spectrometers at short and long wavelengths (SWS and LWS respectively), used a significant fraction of their guarantee time to study YSOs and outflows spectroscopically. In here, I will briefly review some of their main findings, particularly the detection of water, H$_2$ rotational emission lines and the presence of other complex molecules. I will present new spectroscopic results on HH 1-2, HH 7-11 and Cep E, and their sources. And finally, I will discuss some of the general trends derived from these observations and their relevance in understanding the emission from these objects using J and C shock models.

Key Words: INFRARED—ISM: JETS AND OUTFLOWS — LINE:PROFILES

1. INTRODUCTION

After years of planning and developing the Infrared Space Observatory (ISO) was launched in November of 1995, carrying four state-of-the-art instruments and new mid/far infrared detectors. Over the next two and half years ISO provided us with a wealth of incredible observations and a revolutionary view of the infrared universe. It was the first time that we could look at mid/far infrared wavelengths with such sensitivity and angular resolution, and of course, a great opportunity to advance our knowledge on star forming regions and related objects. For the spectroscopic study of outflows, jets and their sources it meant the possibility: (1) to determine the physical conditions of the atomic/ionic/molecular gas, (2) to describe in more detail their shock/ionization structure, (3) to understand the overall energy budget, (4) to study the relationship between the sources and the emitted spectra from their outflows, and (5) to analyze the global trends provided by a bigger sample of objects.
1.1. ISO Instruments

ISO had a 60cm mirror and four instruments that were kept at temperatures of 2-8 K using a large cryo-vessel with over 2000 liters of superfluid Helium (Leech & Pollock 2000). A camera (ISOCAM), a photometer (ISOPHOT) and two spectrometers at short (SWS) and long (LWS) wavelengths were the four scientific instruments aboard ISO. ISOCAM and ISOPHOT had both spectroscopic capabilities, CAM with a Circular Variable Filter (CVF) mode, and PHOT with Phot-S mode. The four instruments had a 3' unvignetted field of view (FOV). Some of the main characteristics of these instruments are the following. ISOCAM was a two channel camera with two InSb 32×32 arrays which covered a wavelength range from approximately 2.3-5.1µm (short) and 5.0 - 17.3µm (long). Each channel allowed four different magnifications (1.5, 3, 6 and 12″/pixel), and in the CVF mode had a spectral resolution R = ∆λ/λ = 40 (Sibemorgen et al. 1999). The Short Wavelength Spectrometer (SWS) covered the wavelength range 2.38-45µm, with spectral resolutions from R = 400 (low resolution grating spectrum) to R = 20,000 (Fabry-Perot). It had different apertures depending on the wavelength region of the grating: at the short range (2.38-12µm) 14″×20″; at the long range 14″×27″ (12.27,5µm), 20″×27″ (27.5-29µm) and 20″×33″ (29.0-45.2µm). At least 4 different types of detectors were used in the grating mode: InSb (2.38-4.08µm), Si:Ga (4.08-12.0µm), Si:As (12.0-29µm) and Ge:Be (37-48µm) (Leech, de Graauw et al. 2000). The Long Wavelength Spectrometer (LWS) covered the wavelength range 43 - 196µm, with spectral resolutions from R = 200 (medium resolution grating spectrum) to R = 10,000 (Fabry-Perot). It had a circular FOV of ∼ 80″, and three different types of the detectors were used GeBe (43-50.5µm), Ge:Ga (49.5-110µm) and stressed Ge:Ga (103-196µm) (Gry et al. 2000).

1.2. Key Programs on Star Formation, Outflows, Jets and their Sources

ISOCAM, SWS and LWS dedicated a substantial fraction of their guarantee time to carry out spectroscopic observations of jets, outflows and their sources. The ISOCAM group led by Sylvie Cabrit obtained nearly 100 observations in their project to study the mid-infrared emission associated with energetic bipolar outflows and the circumstellar dust halos around YSOs. One the scientific goals of this project was to detect the [Ne 11] 12.8µm emission line, as an indicator of relatively high velocity shocks (≥ 60 km s⁻¹), as well as to analyze the effect of the UV field created by such shocks on the nearby dust particles.

The programs of Pre-Main Sequence stellar evolution and the nature of YSOs of the LWS consortium were led by Paolo Saraceno. These programs obtained more than 200 observations, including several full grating SWS spectra as well, of objects as classical T Tauri, Herbig Ae/Be and FU Orionis stars (Benedettini et al. 2000; Giannini et al. 1999; Lorenzetti et al. 1999, 2000; Nisini et al. 1999; Spinoglio et al. 2000).

The SWS team had several projects to study the nature and evolution of interstellar dust, both in the dense environment associated with molecular clouds and low mass protostars, as well as that related with intermediate and massive young stars. Some of the topics studied by the researchers working with them (e.g. W. Van Dishoeck, D. Whittet, and P. Waselius) explored different aspects of the gas-phase and solid (ices) chemistry of species such as H₂O and CO₂, and the chemical state of molecules like OH, C₂H₂, CH₃ and CH₄. Again, these programs obtained nearly 200 observations, and has lead to the publication of several articles, and at least two very complete PhD. Theses by A. Boogert (“The Interplay between Dust, Gas, Ice and Protostars”) and M. van den Ancker (“Circumstellar Material in Young Stellar Objects”).

Besides these GTO projects, textually hundreds of observations in the Open Time were awarded to study problems on star formation and outflows. All the ISO data became public in December 1998, making available over 30,000 scientific observations, the result of approximately 1000 individual programs.

2. THERMAL WATER EMISSION

Among one of the most significant results obtained by ISO was the detection of water in active star forming regions. The theory already had predicted that in molecular shocks or magneto-hydrodynamic C-type shocks (Fig. 1), at relatively high densities (10⁴ – 10⁵ cm⁻³), there was a range in velocity (15-40 km s⁻¹) in which water was the most important coolant (Draine et al. 1983). Under such conditions the shocks eroded ice mantles from the dust grains, returning the H₂O to its gas phase and making available several transitions to release the energy in the far infrared. One of the most striking examples of this process detected by ISO was HH 54 (Liseau et al. 1996), where LWS found 20 or more ortho and para-water emission lines and such that n(H₂O)/n(H₂) = 10⁻⁵, i.e. a lot higher than the expected value in quiescent molecular clouds (10⁻⁷).
Fig. 1. Fractional cooling in MHD molecular shocks (C-shocks)[from Draine et al. 1983]. At high densities and velocities H$_2$O, H$_2$ and [O I] dominate the overall cooling.

Fig. 2. Emission spectra from a MHD molecular shock (C-shock) at 40 km s$^{-1}$, n(H$_2$) = 10$^5$ cm$^{-3}$, B=447µG of the main molecular species from 1 - 2000µm [from Kaufman & Neufeld 1996]

Fig. 3. ISO SPECTROSCOPY OF YSOS

ISO SPECTROSCOPY OF YSOS

Fig. 3. ISOCAM CVF image of HH 7-11 at H$_2$ (0,0) 6.91µm(continuum subtracted). The emission from this flow in the mid-IR is dominated by H$_2$ pure rotational lines. Spectra from individual knots are shown in detail. FOV~90$''$.

10$^{-6}$), and with a cooling comparable to the mechanical energy of the outflow (10$^{-2}$L$_\odot$).

Another important example was that of Orion BN-KL object (Harwit et al. 1998), where LWS Fabry-Perot observations detected 8 different transitions, with an abundance n(H$_2$O)/n(H$_2$) = 5 × 10$^{-4}$, in agreement with the latest theoretical models of the emitted spectra (Fig. 2) by C-shocks (Kaufmann & Neufeld 1996).

3. HH 7-11 OUTFLOW

The bipolar outflow defined by the HH 7-11 system is one of the brightest and best studied. Its redshifted outflow lobe is invisible at optical wavelengths, and so the study of this object permits to compare the properties of embedded outflows with those of optical HH objects. We have analyzed recently the mid/far infrared physical characteristics of HH 7-11 using SWS and LWS observations (Molinari et al. 2000). We found atomic ([O I] 63µm and 145µm, [Si II] 34.8µm) and molecular (H$_2$, CO and
H2O) emission lines along the bipolar flow. Indeed, there was no significant difference in their properties between the optical and the invisible outflow component. We determine that emission could be explained by a combination of J and C-shocks with velocities of 20 – 50 km s\(^{-1}\) and preshock densities of 10\(^4\) – 10\(^5\)cm\(^{-3}\). The SWS and LWS have a limited spatial resolution because of their apertures, and so the CVF ISOCAM observation of HH 7-11 provide further information on its emission properties.

Fig. 3 shows the outflow in the pure rotational line of H\(_2\) S(5) emission at 6.91\(\mu\)m (a single data cube plane) together with the spectra obtained at each pixel, including HH 7, 8 and 10. We notice that (i) the spectra are dominated by the H\(_2\) pure rotational lines S(7) through S(2), (ii) that the morphology of the system is almost identical to that of H\(_2\) (1,0) S(1) emission at 2.12\(\mu\)m, and (iii) behind HH 10 close to the position of HH 11, there is a trace of [Ne II] 12.8\(\mu\)m. This presence of [Ne II] indicates J-shocks with velocities \(\geq 60\) km s\(^{-1}\), a bit higher than that 40-50 km s\(^{-1}\) inferred from optical spectroscopic measurements (Solf & Böhm 1990). The H\(_2\) rotational lines are consistent with our previous findings (Molinari et al. 2000) of the excitation temperatures (\(\sim 500 – 800\)K) and column densities (\(\sim 2 – 12 \times 10^{19}\)cm\(^{-2}\)) (Noriega-Crespo et al. 2001).

4. CEPHEUS E OUTFLOW

Another example of an embedded/optical outflow is that of Cep E. A bright knot in the southern outflow lobe is visible in H\(_\alpha\) and [S II] 6717/31, and known as HH 337. Some of the interesting characteristics of Cep E is that appears to be driven by an unique Class 0 protostar (Lefloch et al. 1996), and the outflow itself is very young, with a dynamical age of \(\sim 3000 – 5000\) years. Cep E was observed with ISOCAM CVF and LWS in full grating mode, and we have recently analyzed these observations (Morot-Martin et al. 2000). Fig. 4 shows the CVF image in the S(5) (0,0) emission at 6.91\(\mu\)m, with the spectrum at each pixel. We notice that both outflow lobes are dominated by H\(_2\) pure rotational emission lines, and surprisingly the IRAS 230111+6126 source is detected. Also that this emission is remarkable similar to that at 2.12\(\mu\)m (Eislöffel et al. 1996; Ayala et al. 2000). In this case, we found T\(_{ex}\) \(\sim 950 – 1300\)K and N(H\(_2\))\(\sim 1 – 3 \times 10^{19}\)cm\(^{-2}\), i.e. a bit higher temperatures and smaller column densities than in HH 7-11.

The LWS spectrum of the North and South outflow lobes had more than 20 molecular lines of CO, H\(_2\)O and OH (Fig. 5). From the CO, H\(_2\)O and H\(_2\) coolings we determine that the FIR spectra was generated by C-shocks at 20-30 km s\(^{-1}\). The [O I] 63\(\mu\)m and [C II] 158\(\mu\)m fine structure emission lines were also detected with similar strengths, indicating contamination by photodissociation in the [C II] line. The corrected [O I] 63\(\mu\)m collisionally excited line required J-shocks at \(\sim 20 – 30\) km s\(^{-1}\) to be explained. Water was overabundant by factors of \(10^2 – 10^3\), i.e. consistent with Cep E low excitation and youth.

5. HH 1-2 OUTFLOW

The brightest and well studied HH 1-2 system, was also observed by ISO with SWS medium resolution, LWS full grating, and CAM CVF. We are in the process of analyzing these data (see e.g. Cenicharo et al. 1999). Unlike HH 7-11 or Cep E, the HH 1-2 objects are high excitation objects (Fig. 6), i.e. with shock velocities of \(\sim 100\) km s\(^{-1}\), enough to produce high ionization [O III] \(\lambda 5007\) emission. Unfortunately the observations of HH 1 have been “contaminated” by the bright Cohen-Schwartz source that lies nearby along the outflow. The H\(_2\) pure rota-
Fig. 5. Full grating LWS spectra of Cep E North and Cepe E South. The spectra are rich in CO, H$_2$O and OH emission lines. [O I] 63$\mu$m & [C II] 158$\mu$m are detected and equally strong.

Fig. 6. A comparison of HH 1-2 and Cep E outflows in the FIR to stress the difference between a high excitation optically visible object (HH 1-2) and a low excitation embedded one (Cepe E).

Fig. 7. ISO CAM CVF (4-17$\mu$m) image of HH 2 & VLA 1 region [from Cernicharo et al. 1998]. The emission of HH 2 contains H$_2$ (0,0) rotational lines as well as [Ne II] 12.8$\mu$m & [Ne III] 14.5$\mu$m. Dust emission from the jet is also detected.

6. CLASS 0/I SOURCES

A very nice result from the ISO observations came from the CAM CVF observations towards Class 0 sources. A Class 0 source, by definition, is a true protostar with the peak of its spectral energy distribution at sub-mm or FIR wavelengths. They are deeply embedded inside an “envelope”, detected in many cases thanks to their powerful bipolar outflows. Our first CAM observations of Cep E detected, at mid infrared wavelengths, the driving source (Noriega-Crespo et al. 1998), presumably a Class 0 source. The CVF observations confirmed
Fig. 8. A sample of Class 0/I sources showing their similarity at mid-IR wavelengths [from Cernicharo et al. 2000]

this detection and displayed a series of spectral absorption features between 5-17µm (CH$_4$ at ∼7.5, Silicates at 9-10µm, and CO$_2$ at 14-15µm) closer to those expected from a more evolved Class I source. We found a similar result for the VLA 1 source in the HH 1-2 outflow and other well known class 0 sources, like NGC1333-IRAS2 or L1448-N (Cernicharo et al. 2000). The difference with respect to a source like IRAS23011+6126, is that the absorption features are so deep, that what is left in the mid-IR SED are a series of emission windows at ∼5.3, 6.6 & 7.5µm (see Fig. 8). In the case of VLA 1, for instance, we can reproduced the mid-IR SED with a object of 4AU in size at 700K and an extinction of $A_V = 80-100$ magnitudes (soft line in Fig. 8).

7. GENERAL TRENDS: EXAMPLES

7.1. Cooling from C-shocks

When the ISO data archive became public in December 1998, it was clear that one could have access to a large sample of objects and able to ask more global questions about the behavior and energetics of outflows, jets and their sources. An example of this approach was carried out by Paolo Saraceno and its group based on LWS observations of Class 0–III sources (Saraceno et al. 1997). In Fig. 9 we used a similar idea (see e.g Spignolio et al 2000) to determine the shock velocity in a series of outflows, based on their H$_2$O, [O I] 63µm and CO cooling when compared with the predictions from C-type shocks (Draine et al. 1983; Kaufmann & Neufeld 1996). At first approximation the cooling from these species defines a narrow range of shock velocities ($10 - 20$ km s$^{-1}$) and densities ($\log n($H$_2)$= 4.5 – 5.5), with perhaps a couple of exceptions (IC1396N & IRAS 16293). If we approximate the working surfaces of the jets/outflows by bowshocks, then the above result suggests that the molecular emission arises away from the stagnation region, further “downstream” and along the bow shock wings. A result compatible with the numerical hydrodynamics simulations of working surfaces, with parallel integrated chemistry (Williams 2001; Lim et al. 1999).

7.2. H$_2$O from Circumstellar Envelopes

LWS observations have been used recently as well (Ceccarelli et al. 1999), to study the correlation between H$_2$O thermal emission arising from protostellar sources and their 1.3mm continuum fluxes or SiO millimetric emission. The idea is to try to distinguish if the H$_2$O emission comes from the outflows (SiO as a tracer) or closer to the source (an envelope, with 1.3mm flux as a tracer). Although the results are far from conclusive (see e.g. Neufeld et al. 2000), from a sample of 7 YSOs, 5 seem to correlate quite well with their 1.3mm fluxes (Fig. 10), but not with the SiO emission. The suggested explanation is that
the H$_2$O lines originate from the warm inner region of infalling envelope, with accretion rates of a few $10^5 M_\odot/\text{yr}$.

8. SUMMARY
Astronomically ISO was a very successful mission, and for star forming regions, stellar jets, outflows and their sources, it meant hundreds of new observations at mid and far infrared wavelengths. I have shown a small sample of the spectroscopic results on some prototype outflows, as HH 1-2, HH 7-11 and Cep E, that have illustrated the different ISO observational modes, and the physical conditions that can be derived from them. It is clear that molecular cooling at FIR wavelengths is an important component of the overall energy budget of outflows and jets. One of the nice surprises from ISO has been the possibility to observe deeply embedded sources at mid-IR wavelengths, since this opens a door for ground based observations with large telescopes of some of the less known phases of the star formation process.

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