

## High Resolution Studies of Molecular Hydrogen by Means of Near-Infrared Fabry-Perot Imaging

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**Abstract.** We present a study of the velocity profiles of the  $v=1-0$  S(1) transition of molecular hydrogen ( $H_2$ ) towards the star forming region of OMC-1. A three dimensional data cube is presented which displays the spatial distribution as well as the velocity structure of the  $H_2$  emission. A brief description of the data acquisition, reduction and analysis is given.

The three dimensional aspect of the data has allowed us to re-examine the kinematic nature of the region. The results reveal a number of isolated sources which possess asymmetric velocity profiles which can be modelled by bow C-shocks. The implication is that these sources are compact knots of material which were involved in some explosive event, possibly associated with the luminous source IRc2, and are ploughing into the dense

molecular disk around IRC2. It is likely that these bullets are associated with those discovered by Allen & Burton (1993).

## 1. Introduction

Embedded behind the HII region M42, in the Orion Molecular Cloud (OMC-1) lies what is perhaps the most intensely studied regions of ongoing star formation. There have been several observations which have indicated OMC-1 to be a site of high velocity motion from a central source. CO and H<sub>2</sub> maps have revealed the presence of red- and blue-shifted components (Erickson *et al.* 1982; Beckwith *et al.* 1978). Spectroscopy of the H<sub>2</sub>  $v=1-0$  S(1) line at 2.122 $\mu$ m has shown it to have a velocity width of  $\sim 150$  km s<sup>-1</sup> (Brand *et al.* 1989) and several Herbig-Haro (HH) objects have been found in the region with line widths up to  $\sim 400$  km s<sup>-1</sup> (Axon & Taylor 1984).

Recently, Allen & Burton (1993) have mapped the region in [FeII] 1.64 $\mu$ m and H<sub>2</sub> emission, both lines being sensitive to shock activity. They found at least 20 hollow structures in the H<sub>2</sub> emission, typical of classic bow shock structure, and compact [FeII] emission knots associated with the tips of the H<sub>2</sub> structures. This complex of knots and wakes requires compact clumps of material to have been ejected over a wide opening angle in a recent explosive event.

While narrow band imaging is useful in determining the morphology of the H<sub>2</sub> emission, it does not yield any information about the kinematics of the gas. However, with the infrared techniques available to us today and with the use of a high resolution Fabry-Perot etalon, it is possible to obtain images which possess both high spatial and spectral resolution, providing a unique method with which to investigate the kinematics of the gas at the heart of the explosion described by Allen & Burton.

## 2. Observations

A velocity cube of the emission of the  $v=1-0$  S(1) transition of H<sub>2</sub>, covering the bright shocked region of OMC-1 was obtained, at the UKIRT on the nights of 29 January 1989 and 7-10 January 1990, with 0.6 arcsec pixel scale with 14 km s<sup>-1</sup> velocity resolution. Each cube was acquired by stepping a Queensgate Instruments Fabry-Perot (FP) etalon through its free spectral range (FSR  $\sim 445$  km s<sup>-1</sup>), taking an image at each step and then stacking the final number of images together to form the cube. The small angular difference between the centre and edge of the array results in a shift in the transmitted velocity phase across the array for each individual image. The magnitude of this phase shift is determined by a phase calibration cube, obtained by scanning the FP through its FSR while observing a diffused arc lamp line. The line appears as a ring on the array whose radius varies as the FP is scanned. Using this phase cube, one can then determine the amount of shift which is necessary at each pixel position such that each plane of the cube has a constant wavelength (Bland-Hawthorn & Tully 1989).

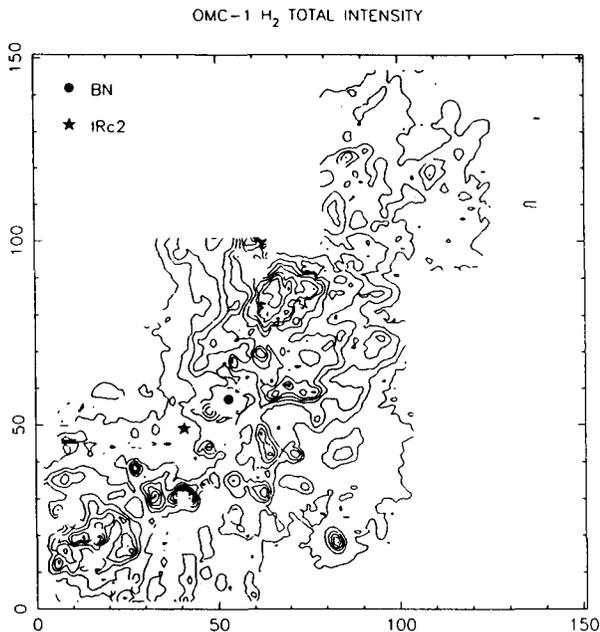


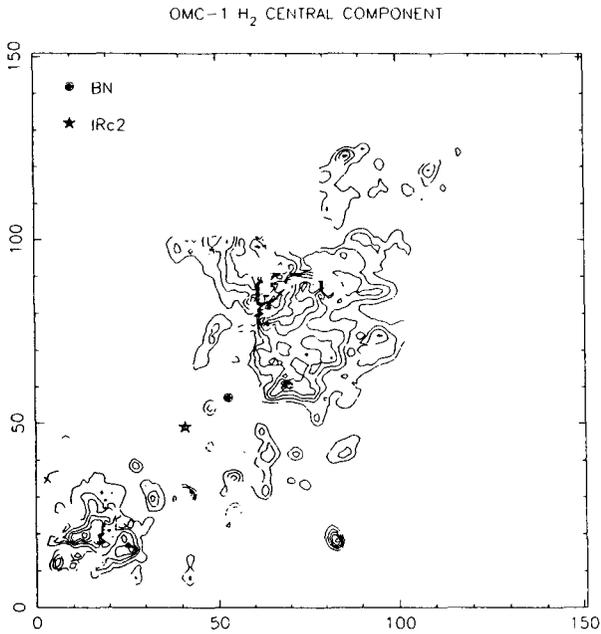
Figure 1. The total integrated H<sub>2</sub> intensity from the data cube. The positions of BN and IRC2 are marked for reference.

No absolute flux calibration was attempted. The bright continuum source, BN, was used to calibrate transmission variations during the night. The 5 cubes were then mosaiced, registering in both spatial and spectral directions, producing a data cube of some 150 × 150 spatial pixels and approximately 15,000 velocity profiles. These profiles were analysed by fitting three Lorentzian (ie. Cauchy) profiles; the three components were characterised as either forming the central, blue or red component of the line profile.

### 3. Results

These observations represent the most comprehensive study to date of both the distribution and velocity structure of molecular hydrogen emission in OMC-1.

In Figure 1, the total H<sub>2</sub> intensity is presented. The total intensity is given by summing the intensities in the central, blue and red components. The positions of the Becklin-Neugebauer (BN) object and the infrared luminous source IRC2 are marked for reference. The image is the familiar picture of the H<sub>2</sub> emission showing the Peak 1 and Peak 2 emission maxima to the NW and SE of BN and IRC2 (eg. see Beckwith et al. 1978). Further to the NE, a part of the so-called 'finger' region (Taylor et al. 1984) can be seen. This position is coincident with at least 3 of the [FeII] bullets seen by Allen & Burton (1993), including M42-HH1 (Axon & Taylor 1984) which is not bright in H<sub>2</sub> and does not uniquely register above the background H<sub>2</sub> emission in these images.



**Figure 2.** The H<sub>2</sub> emission of the dominant central component minus the characterised foreground emission. The image clearly shows two lobes of a bipolar outflow which are diametrically opposed, with IRc2 at their centre of symmetry.

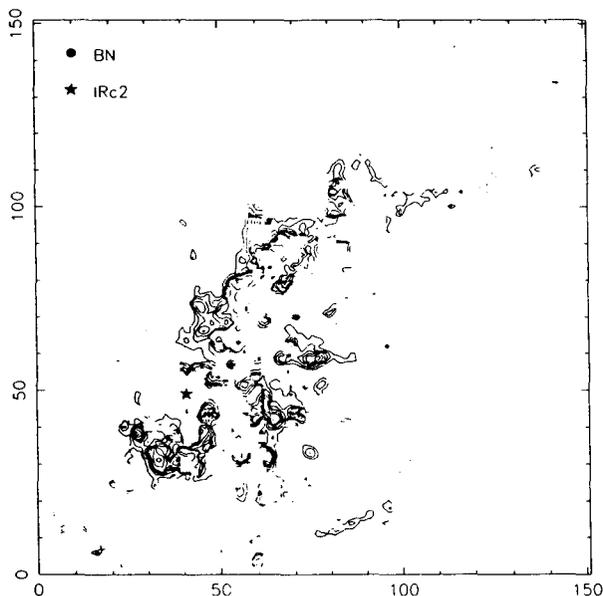
OMC-1 H<sub>2</sub> BLUE COMPONENT

Figure 3. The H<sub>2</sub> emission from just the blue component of the velocity profiles. The spatial distribution is quite clumpy, showing a number of isolated condensations clustered about IRC2.

One of the interesting features in this image is the presence of a constant emission component which seems to pervade across the whole region. To characterise the source, velocity and height of the component, a region which is free from other sources of emission was chosen, covering the region between pixels (79,24) and (99,48). The velocity and width of this component were found to be +13 and 35 km s<sup>-1</sup> respectively. The height of this component was then removed from the dominant central component over the whole region as a first order subtraction of the constant foreground component. The result is shown in Figure 2, which shows very clearly the two diametrically opposed lobes of the bipolar outflow with IRC2 at their centre. The empty space between the inner edges of the lobes coincides with the outer boundaries of the dense molecular disk which is seen in CS emission (Murata et al. 1991). The origin of the foreground component may be from a pressure wave being driven by the outflow into the surrounding molecular cloud.

In Figure 3, we show a plot of the intensity of the blue component of all the profiles. Essentially, this figure shows the spatial distribution of excited molecular hydrogen which exhibits a degree of asymmetry in the velocity profile. What is immediately seen is that this figure in no way resembles the traditional outflow picture we see in figures 1 and 2. Instead, the emission appears very clumpy with several condensations clustering about IRC2. Comparison with Figure 2 would seem to suggest that the majority of these sources are embedded within the molecular disk.

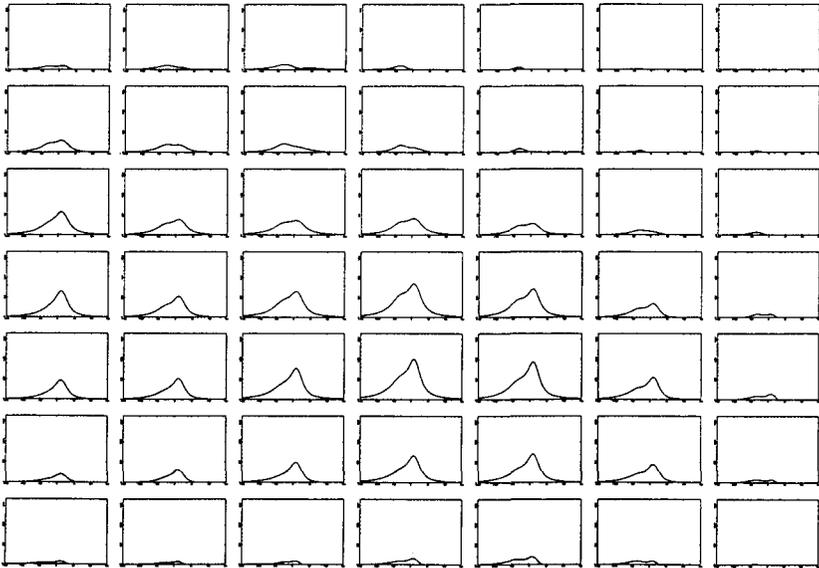


Figure 4.  $H_2$  velocity profiles from one of the condensations in Figure 3. The profiles have had the profile characterising the foreground component removed from them.

The great advantage of the Fabry-Perot data cube is that for each spatial position one also has the spectral, or in this case velocity, information. This allows examination of the velocity structure of each of these condensations and hence the origin of their emission. Figure 4 shows the fitted profiles from one of these condensations, at pixel position  $\sim (73,33)$ . Contamination from the foreground component has been removed, however, this time by removing the complete profile characterised by the parameters described above. These profiles are remarkably similar to those produced by a bow shock (eg. see Hartigan *et al.* 1987). In Figure 5, the resultant profile is shown of the total emission from the profiles given in Figure 4 (produced by simply summing the emission in each velocity channel for each of the pixels). This profile can now be directly compared to the  $H_2$  bow shock profiles in the models by Smith *et al.* (1991). Allowing for the different convolutions - instrument profile of the data is Lorentzian while the models of Smith *et al.* have been convolved with a gaussian - the profile in Figure 5 implies that the bullet in Figure 4 is travelling between  $30^\circ$  and  $60^\circ$  to our line of sight. For each of the well resolved condensations in Figure 3 a solution of the bow shock model can also be found which satisfies the data.

#### 4. Discussion

Emission from a bow shock is usually attributed to the interaction of a collimated jet with ambient molecular material, as is the case for a majority of the HH

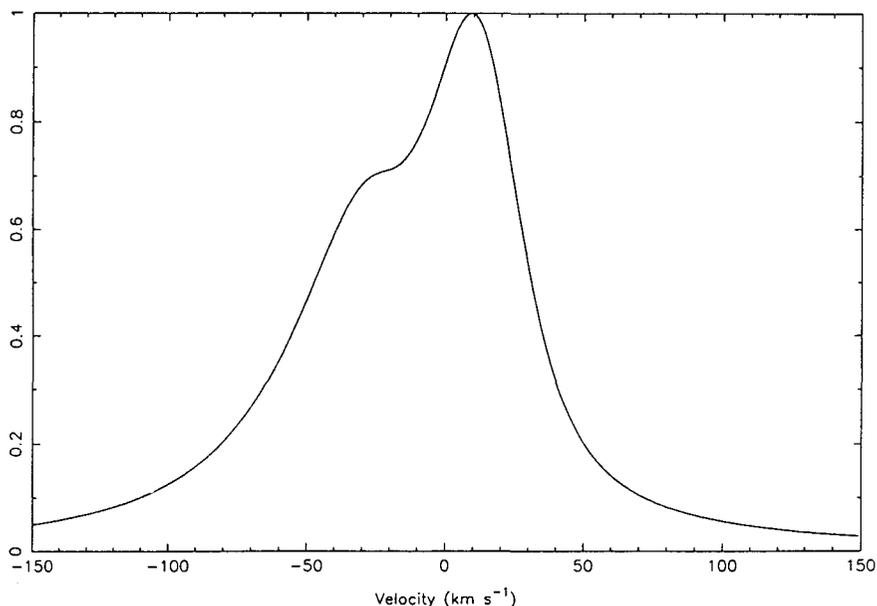


Figure 5. Total emission profile of the profiles in Figure 4. This allows us to directly compare with the model profiles of Smith et al. (1991).

objects that have been discovered. However, in this case, it is difficult to make such a claim as one would need to collimate a complex of multiple jets from the one source, IRc2. A much simpler solution exists if one also considers the bullets discovered by Allen & Burton. Bow shocks are also naturally formed around bullets, as the Allen & Burton images dramatically show. It is reasonable to assume that the 'explosion' which formed the bullets was isotropic, with bullets ejected in all directions, and not just confined to ejections along the bipolar axis. In this scenario it is then straightforward to marry these observations with those of Allen & Burton to form one coherent picture if one assumes that the bow shock profiles that are found in this data set are also formed by bullets, ploughing their way through the dense molecular disk. Although the Allen & Burton bullets are at much higher velocity ( $\sim 300 - 400 \text{ km s}^{-1}$ ) than the bullets found here, the difference is easily reconciled as the Allen & Burton bullets must have travelled along the poles of the disk, thus helping to retain their high velocities. Furthermore, there is the presence of a bipolar outflow here which probably offers an evacuated cavity for those bullets travelling close to the bipolar axis. The bullets that are found in the FP data cube and are travelling through the molecular disk must have experienced a greater degree of deceleration by virtue of the fact that they are traversing a much denser medium. It is therefore natural not to find them at such distances and velocities as their polar counterparts.

## 5. Conclusions

The power of the technique of using a Fabry-Perot to assimilate a data cube at high spatial as well as spectral resolution has allowed us to redefine our knowledge of the important star forming region in Orion, OMC-1. The presence of a bipolar outflow is confirmed. We also find a series of bullets which are traversing through the dense molecular disk. Together with the bullets discovered by Allen & Burton, the overall morphology of this complex of bullets suggests that a single explosive event occurred some 1000 years ago (Allen & Burton 1993), sending the debris in all directions, producing the H<sub>2</sub> and [FeII] bullets we see today.

## Discussion

*J.P. Maillard:* What are the proofs that IRc2 is the source of the jets?

*A. Chrysostomou:* There is no "proof" as such that IRc2 is the source of the outflow/bullets system. However, it is the best candidate, and definitely, there is evidence suggesting that it is most probably the source. For instance, it is at the point of symmetry of the outflow lobes presented here and the CO outflow lobes. Furthermore, Allen and Burton (1993) have attempted to trace back the trajectories of the bullets in the "finger" region and find that the origin is within  $\pm 5$  arcsec about IRc2. It is deeply embedded behind a thick molecular disk, as expected for YSO with collimated outflows, and finally, there is no other obvious source in the vicinity.

*J. Kavelaars:* What is the physical scale of these bullets? The ones stuck inside the disk. Perhaps these relate to similar observations in Cepheus A (observations by V.A. Hughes at Queen's University)

*A. Chrysostomou:* The average size of these bullets is approximately 100 A.U. i.e. the same order as the solar system size. It would be very interesting to see if these relate to the observations of Cepheus A. The reason being that if our estimates are correct, then this explosive event happened some 1000 years ago. This is a very small fraction of the time it takes for a star to form, which means that we are very fortunate to have witnessed this event in Orion. However, if this extreme event is common in regions of high mass starformation, then it will prove very important if we could find similar occurrences in other regions.

*T. Magakian:* Have you any estimations for the mass and characteristic times of these "bullets"?

*A. Chrysostomou:* Yes we do have estimates for the mass of these objects, it is around  $10^{-5}$  solar masses. If we believe that the bullets were found here are co-eval with those found by Allen and Burton (1993) then the explosive event responsible for them occurred approximately 1000 years ago. A very short time!

*G. Cecil:* 1. Have you correlated your H<sub>2</sub> datacube peaks with the H radio recombination cubes?

2. Even without spectrophotometry, can you estimate the fraction of emission-line flux within the "bullets" versus the diffuse gas?

A. *Chrysostomou*: 1. I have only made an "eyeball" comparison between the radio maps of Felli et al. and our data. There is a possibility of maybe a couple of coincidences.

2. I have not as yet investigated the energetics of the whole system. It would certainly be interesting to determine the fraction of energy deposited into the molecular cloud by the bullets and by the outflow, but this may prove difficult.

### References

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