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Emission Lines from Jet Flows (Isla Mujeres, Q.R., México, November 13-17, 2000)
Editors: W. J. Henney, W. Steffen, A. C. Raga, & L. Binette

KINEMATICS OF YSO MOLECULAR HYDROGEN OUTFLOWS[1]

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RESUMEN

Describimos observaciones de la línea de 2.12 μm de H_2 para los flujos moleculares en OMC-1, HH 211, HH 212, DR21, CephA, y S187-IR, que forman parte de un catálogo de cinemática en H_2 en preparación. Las observaciones están siendo realizadas con la cámara infrarroja CAMILA y un etalón Fabry-Pérot en el telescopio de 2.12 m en el Observatorio Astronómico Nacional en San Pedro Mártir. Con una resolución espectral de 22 km s^{-1} (FWHM) hemos podido determinar las propiedades globales de la cinemática de estas fuentes. Demostramos que estas son consistentes con modelos teóricos tales como el de flujos impulsados por chorros. Se comenta también sobre la existencia de una relación flujo contra velocidad, de gran similitud a la observada en la línea de CO.

ABSTRACT

As part of an on-going kinematical survey of molecular outflows, we describe observations of the 2.12 μm line of H_2 for objects such as OMC-1, HH 211, HH 212, DR 21, Ceph A and S187-IR. The observations were made with the CAMILA IR-camera and an imaging Fabry-Pérot etalon at the 2.12 m telescope of the Observatorio Astronómico Nacional in San Pedro Mártir. A 22 km s^{-1} (FWHM) resolution allows us to determine the global kinematics of these sources. We show that many of them are consistent with theoretical models such as the jet driven molecular outflow paradigm. A flux versus velocity relation, similar to the one observed for CO outflows, is revealed by H_2 velocity structure.

Key Words: **ISM: JETS AND OUTFLOWS — ISM: KINEMATICS AND DYNAMICS — ISM: MOLECULES — STARS: FORMATION**

1. INTRODUCTION

The infrared camera CAMILA (Cruz-González et al. 1994) is conveniently mounted on a cooled optical bench, which is maintained at a constant temperature by a circulating cooling fluid. Its configuration allows for an easy interaction for the set up of different experimental devices. This has allowed us to install and operate a Queensgate scanning Fabry-Pérot interferometer (Salas et al. 1999, S99), at the collimated beam of the optical train. The finesse of the etalon allows for a FWHM resolution of 22 km s^{-1} at 2.12 μm, which we sample at 9.8 km s^{-1} intervals. This has proven enough to get precision of $\simeq$ 3 km s^{-1} in line center determinations, and we have been involved in an H_2 outflow kinematics survey since 1997.

2. H_2 OUTFLOWS

To date we have observed about a dozen objects, from which we have selected a fraction for this paper. The objects chosen cover a wide range in collimation degrees and mass loss rates. In the past, the kinematics of H_2 in molecular outflows has been studied for some particular objects, mainly using 1-D slit spectrometers, although in a few cases 2-D interferometers have been used. However, to our knowledge, this is the first comprehensive 2-D survey of kinematics of H_2 in molecular outflows. Figure 1 (see plate) shows the sample of objects presented for this work. This true-color image is a combination of 3 separate images (red, green, and blue), each representing the emission in a different velocity range. In all cases, the velocity decreases in the sequence red-green-blue but the actual values of the ranges vary between the objects shown. The reader is referred to the cited works for details.

The first object that we studied was the classical and complex OMC-1 region (S99), which in many senses is the prototype of outflows. That is, as any good prototype of a class of objects, it is the first one to be discovered by its prominence while it is different from all the other objects in the class. And what makes this one different from others is that this particular outflow is younger than the time scale for the destruction of its immediate environment, by

[1]Based on observations obtained at the Observatorio Astronómico Nacional at San Pedro Mártir, B.C., México.

the action of its own driving momentum. It is in the process of developing a wind-driven shell, but it has not yet developed the velocity law expected for a shell. This has been shown by S99 to be the case, since the radial velocity law is well-fitted by a $1/r$ profile. Although the morphology of the outflow region is slightly bipolar, the $1/r$ velocity law holds in any direction from the center, considering either BN or IRc2 as the exciting source. This is indicative of a very wide wind, which S99 have modeled as spherically symmetric, while the ISM around it has been modeled as a set of molecular clumps with constant density. The interaction of the wind with the clumps drives a secondary shock propagating into the clumps at a speed which is in ram pressure equilibrium with the main shock. This speed decreases as $1/r$ for different clumps at radial distances, r. The model is quite involved with the details of radiation transfer in a clumpy medium, but at the end this simple $1/r$ law describes the first 4 observed radial moments of the intensity-velocity distributions.

As mentioned before, OMC-1 is a special case. The other outflows in the sample will allow for a common treatment, which is different than the one employed for OMC-1. However, a flux velocity relation common to all of them, including OMC-1 will be uncovered.

We turn then to a highly collimated outflow, HH 211. This outflow is presented in Salas, Cruz-González, & Rosado (2002a, S02a). The very nice feature of this object is that it has been observed in another molecule: CO by Gueth & Gilloteau (1999, GG99) with a spatial resolution equivalent to the one used in our NIR studies ($\approx 1''$). This has allowed GG99 to show a close morphological connection between both outflows. S02a shows that there is also a very close kinematical relationship. This is also complemented by another (unexpected) close connection between CO and H_2 outflows in general. Salas & Cruz-González (2002, SCG02) have shown the existence of a flux-velocity relation akin the well known mass-velocity relation (see, for example, Masson & Chernin 1992) for CO outflows. In both cases a power law with velocity, above a certain break point, is observed, and with a similar value for the exponent. This relation is unexpected because, unlike the case for CO emission, in H_2 mass is not proportional to flux alone, but an additional dependency on velocity should be expected, since H_2 arises in shock heated regions, and thus, a quite different value of the exponent should be observed. Whatever the reason, as pointed out by SCG02, this strongly suggests a dynamical similarity for CO and H_2 outflows as well, and adding to the morphological and kinematical similarities for HH 211, S02a decided to test molecular outflow models, which have been traditionally developed for CO outflows, for H_2 outflows. Two possibilities are tested, jet driven outflows (in the approximation of GG99) and wind driven shells as predicted by the X-wind theory and in the equations of Matzner & McKee (1999, MM99).

These models are also applied to the other objects in the sample: HH 211 (S02a); Ceph A east and west, (Salas et al. 2002, S02b), DR 21 (Cruz-González et al. 2002, CG02) and HH 212. In all these cases it is possible to roughly adjust the morphology and the kinematics, in order to obtain a rough estimate of the mass-loss rate of the source (see S02a for an example). In the end, it is seen that although it is not possible to decide whether one or the other model provides a better fit, a lower value of the mass-loss rate is generally obtained using the jet-driven model, which is a more efficient way to accelerate molecular material, and it also gives values more consistent with other estimations in the literature. The flux velocity relation found for HH 211 also holds for the other outflows. The power law is very similar but the value of the break velocity is different (SCG02).

The other outflow described in the paper is the curved molecular outflow in S187-IR (Salas, Cruz-González, & Porras 1998), for which a very complicated velocity law is encountered (Salas, Cruz-González, & Rosado et al. 2000). Although this outflow seems quite collimated, similar to HH 211 and HH 212, it presents a large curvature that makes its trajectory deviate by almost 180 degrees. It has been argued that this curvature is due to the effect of a supersonic side wind, whose origin could be a somewhat large proper motion of the source. Due to its awkward geometry a fit to jet driven or X-wind driven outflow models has not been attempted. However, it is found that the flux-velocity relation is also observed for this outflow.

3. FLUX VERSUS VELOCITY RELATION

The flux-velocity relation (SCG02) is thus seen to be a very common property of molecular outflows traced by the H_2 molecule in its $v = 1\text{–}0\ S(1)$ transition. The break velocity varies apparently in good correlation with the collimation degree of the outflow and the mass loss rate, which can be determined from the fit to jet-driven models of outflows.

The objects that depart from this correlation are OMC-1 and S187-IR. We have proposed (SCG02) that this departure is due, in the case of OMC-1, to the youthfullness of the outflow, and in the case of

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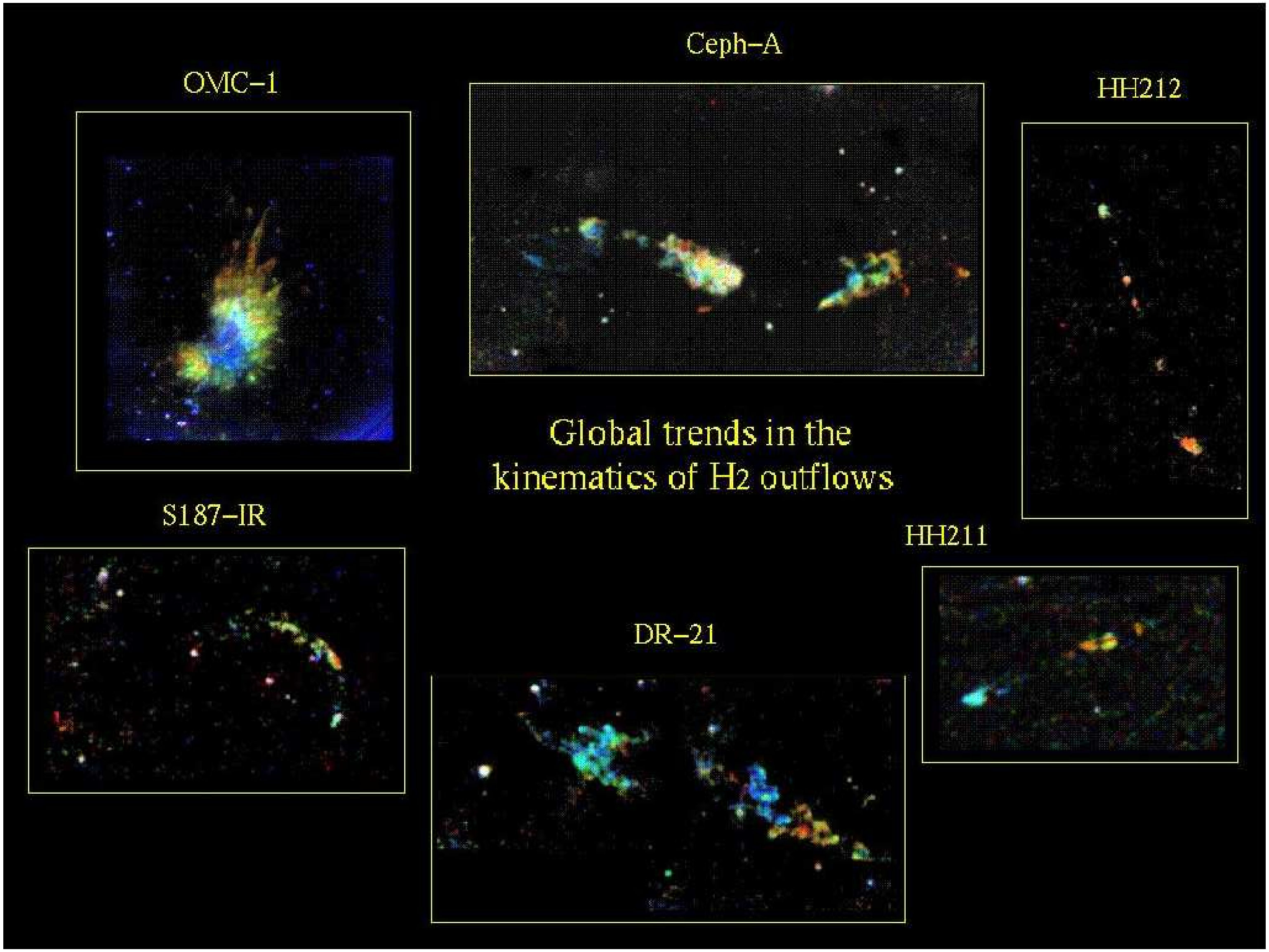

Fig. 1. Color composite H_2 velocity images of YSO outflows. Taken from: S99 (OMC-1); S00 (S187-IR); CG02 (DR21); S02a (HH 211); and S02b (CephA). Note: this figure is available in color in the electronic version of this article, obtainable from `http://www.astroscu.unam.mx/~rmaa/`.

S187-IR, to the fact that the energetics of the system is governed by that of the side wind.

We have proved that 2-D surveys of kinematics of H_2 in molecular outflows are a very powerful tool that may provide contrains on the driving sources of the outflows. The physics revealed by the flux versus velocity relation and its similarity to CO mass versus velocity is yet to be completely understood and explained.

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