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HIGH VELOCITY OUTFLOWS IN THE ORION NEBULA DETERMINED FROM PROPER MOTIONS

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RESUMEN

Las imágenes del telescopio espacial Hubble son de resolución lo suficientemente alta que cuando se comparan las mas recientes con las que datan de diciembre de 1993, se pueden medir movimientos propios hasta unos 10 km s^{-1}. Tales observaciones muestran una gran riqueza de detalles y revelan múltiples sistemas de eyecciones de alta velocidad. Los movimientos propios son particularmente útiles para determinar el origen de las eyecciones. Estas revelan una eyección (HH 625) que se origina de la fuente molecular bipolar de alta velocidad en Orion-S. Quizá lo mas sorprendente es la evidencia de que la mayor parte de las eyecciones observadas en el óptico en Orion aparentemente se originan de una fuente localizada en 5:35:14.56 -5:23:54 (2000) que no posee una contraparte brillante en ninguna de las longitudes de onda observadas.

ABSTRACT

Hubble Space Telescope images are of sufficiently high resolution that when recent images are combined with those going back to December, 1993, one can measure proper motions down to about 10 km s^{-1}. Such observations show a wealth of detail and reveal multiple high velocity outflow systems. Proper motions are especially good for determining the origin of outflows. They reveal an outflow (HH 625) originating from the high velocity bipolar molecular source in Orion-S. Perhaps most remarkable is the evidence that most of the optical outflow in Orion appears to originate from a source located at 5:35:14.56 -5:23:54 (2000) which possesses no bright counterpart at any observed wavelength.

Key Words: **H II REGIONS — ISM: JETS AND OUTFLOWS — STARS: PRE-MAIN SEQUENCE — STARS: MASS LOSS**

1. INTRODUCTION

To make the common statement "the Orion Nebula is one of the best studied objects in the sky" needs to be done once again, as this knowledge is in large part due to the participants in the Texas-Mexico Conference on Astrophysics. Congratulations to my many colleagues attending this meeting. Examination of the proceedings of the seven previous conferences shows how our knowledge has become quite refined, although at the same time leaving many important questions. This situation has been described in a recent review article (O'Dell 2001) and need not be described here.

This article will describe the results of use of recent two-epoch observations with the Hubble Space Telescope's (HST) oldest camera (WFPC2) for determination of motions in the plane of the sky (proper motions) down to a value of 10 km s^{-1} and what those determinations reveal. There have been a number of earlier determinations (Hu 1996; Bally, et al. 2000, henceforth BOM; Doi, et al. 2002, henceforth DOH), but new observations have allowed a time base of up to 8.05 years-hence the new level of accuracy in the results (O'Dell & Doi 2003, henceforth OD).

2. SHOCKS NEAR YOUNG LOW MASS STARS

The shocks associated with well defined pre-Main Sequence (PMS) low mass stars are divided into two classes, those driven by a general wind and those driven by jets. There are finer divisions in both of these classes. In almost all cases the high velocity outflow material is forming a shock with the ambient nebular gas.

The PMS stage of low mass stars seems to be accompanied by a general wind (outflow) phase powered by the accretion of material onto the inner disk region of the protostar. We see one clear example of the shock formed in the object HH 626 (OD), which has a velocity of about 30 km s^{-1}. There are numerous other examples where the source of the outflow arises from photo-evaporation from the proplyd's ionization front. The shock formed with the high velocity wind from θ^1 Ori C appears to be stationary (Graham et al. 2002). In contrast,

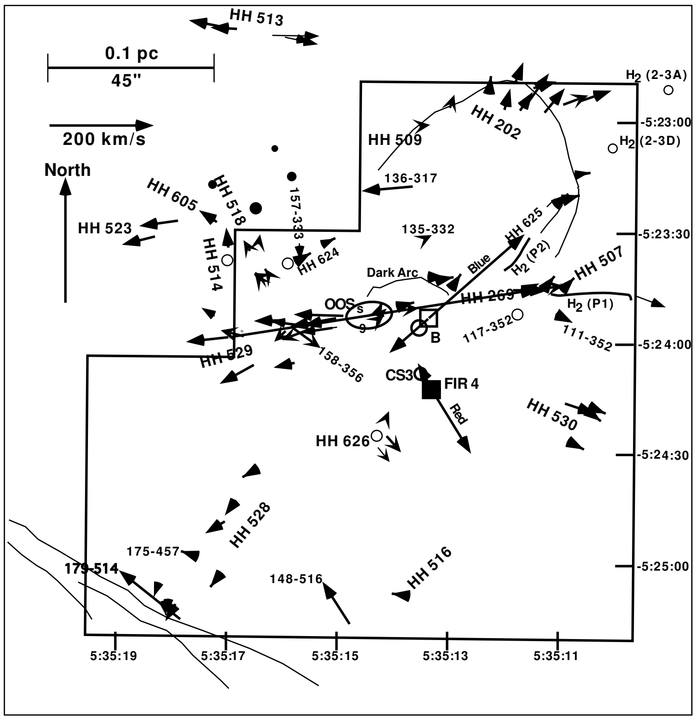

Fig. 1. This cartoon of a 185″x 192″ portion of the Orion Nebula to the south-east of the Trapezium stars shows the proper motions of various sources (after OD). The names of the objects are discussed in the text, except for individual features, which are designated according to the position based system of O'Dell & Wen (1994).

objects farther from θ^1 Ori C will have less photo-evaporation and no irradiation with θ^1 Ori C's wind, yet we see non-moving shocks (BOM), the best example being the east-facing shock associated with LL Ori, a T Tauri star. In this case the two colliding flows are probably the outflow wind of the young star and the nebular gas flowing away from the high density central portion of the nebula.

Jets arising from PMS stars are not uncommon in the cluster stars but there is the peculiarity that most of them are seen as mono-polar, rather than bi-polar (BOM), although the second flow can sometimes be detected at similar velocities but much lower brightness. The common interpretation is that they are all bi-polar, but conditions of irradiation by θ^1 Ori C cause the difference in appearance of the two sides. However, the preferential mono-polarity continues into the study of proper motions, where we see only one example of a bi-polar shock (HH 513; BOM,DOH), but numerous examples of shocks and series of shocks extending in only one direction (HH 509, HH 514, HH 518, HH523, HH 624; BOM, DOH, DO) from their apparent source.

3. HH 625: THE FIRST OPTICAL FLOW ASSOCIATED WITH AN IMBEDDED MOLECULAR OUTFLOW

To the south-west of θ^1 Ori C is the Orion South (Orion-S) region, which has several infrared and radio sources with no optical counterparts. Rodríguez-Franco et al. (1999a, 1999b) have shown there there is a high velocity bi-polar molecular outflow extending from Orion-S with velocities of -140 km s^{-1} towards the north-west and 88 km s^{-1} to the south-east. We would only expect to see optical components associated with the blue-shifted component, because only that flow has a chance of breaking out into the photoionized nebula and we do (OD). We first detected proper motion (about 25 km s^{-1}) at the tip of a shock feature along the blue-shifted direction, then found associated features in H_2 (Kaifu et al. 2000). A projection from the blue-shifted CO flow through the H_2 and moving feature lies exactly along the line occupied by the H_2 features (2-5, and the quadruple object 2-3) found by Stanke, et al. (2002). Orion-S is a region that is essentially a hill on the surface of the nebula (Wen & O'Dell 1995). Evidently the blue-shifted molecular outflow is grazing along the surface of the nebula, producing observable H_2 and optical features. These and other

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features are depicted as a drawing in Figure 1.

In passing it should be noted there there are also optical features (HH 530) that pass through the vicinity of the strongest infrared sources (FIR 4, Mezger et al. 1990 and CS, Mundy et al. 1986) in Orion-S, which give rise to a low velocity CO flow (Schmid-Burk et al. 1990, Gaume et al. 1998)). However, an association with that bi-polar flow is unlikely because of the quite different direction of the CO flow.

4. THE ORIGIN OF THE LARGE SCALE OPTICAL FLOWS

There are several large scale (length about 100″) flow systems in the Orion Nebula. The first known were HH 202 and the close pair HH 203+HH 204 (probably not a true pair as they have different velocities, O'Dell et al. 1997a). More recently, HH 269 has been recognized from images (Walter et al. 1995), radial velocities (O'Dell et al. 1997b), and proper motions (OD). Almost opposite in direction is HH 529, whose presence was originally suggested by the appearance of a series of shocks, but confirmed by their proper motions (BOM). The most recent entry to the list is HH 528, which was not recognized until the motions of its fragmented components were noted (BOM), after which it was easy to see the structure. These objects are also shown in Figure 1.

There may or may-not be a region of common origin of these flows. They are certainly not bipolar flows since all of them (except HH 528, whose radial velocity is unknown) have blueshifts. The alignment of the symmetry axes of HH 202 and HH 203+HH'204 has been used to argue for an association and the presence of nearly linear high velocity features pointed towards them may provide a key to their origin (O'Dell et al. 1997b, Rosado, et al. 2001). The putative HH 203+HH 204 jet also can be traced in the He I 10,830 Å line (Takami 2001). The multiple shocks moving in opposite directions in HH 269 and HH 529 argue that a common source lies between them. The direction of HH 528 is less well defined than the other large objects, but can provide rough information.

When the information from all of these objects is combined, it appears that there is a prime candidate region for a common source. This is called the OOS in Figure 1 (Optical Outflow Source) and is an ellipse centered at 5:35:14.56 -5:23:54 (2000). There are no strong infrared, radio, nor x-ray sources located at this position and the nature of the putative common source is unknown. Certainly the various flows are not co-planar as they all (c.f. the earlier note on HH 528) have blueshifted radial velocities. HH 528 is very low excitation, which probably indicates that it lies near the surface of the nebula. In contrast is HH 203+HH 204, which share the common feature of having no [O III] emission from their shock-tips, but have extended [O III] emission in the direction of θ^1 Ori C. The argument of O'Dell et al. (1997a) is probably correct, this being that these are shocks formed in the foreground veil of neutral material that lies in front of the entire nebula, and that the gas within the shocks is being photoionized by θ^1 Ori C. Similar arguments can be made for HH 202. HH 269 is a combination of high and low ionization optical features, but also has associated H_2 emission (Kaifu et al. 2000). This argues that HH 269 is like HH 625 and is grazing the surface of the main layer of ionization. However, HH 529's shocks are clearly high ionization and represent jet driven shocks occuring in the ionized part of the nebula.

In the sense of having a multiplicity of directions of shocks with an apparent common source, these flows resemble the flows discovered by Allen & Burton (1993) which also have a common origin near the BN-KL region (DOH) and are all blueshifted. In the case of the Allen & Burton features, it is possible that they are due to either multiple "bullets" ejected from a common source or the results of instabilities. If the OSS objects are similar, then a "bullets" model is more likely, although just how such a process can work is now unknown.

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