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DISKS AND OUTFLOWS IN THE ORION NEBULA AS DETERMINED BY THE HST

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RESUMEN

El Telescopio Espacial Hubble ha empezado a jugar un papel importante en la comprensión del proceso de formación estelar en las proximidades de la Nebulosa de Orión. Imágenes recientes de la parte norte de la región muestran que los objetos Herbig-Haro que se conocían previamente tienen una morfología muy irregular y están espacialmente desplazados con respecto a las imágenes infrarrojas. La gran resolución espacial permitirá, además, medir movimientos de expansión con precisión. En la parte sur de la nebulosa observamos a HH 203 y 204 con un detalle sin precedentes, y descubrimos numerosos choques de alta ionización corridos al azul. El descubrimiento más llamativo ha sido el observar que la mayoría de estrellas de masa pequeña de la presecuencia principal tienen materia circunestelar que se hace visible, ya sea porque las partes externas están siendo fotoionizadas, y/o por el oscurecimiento de la luz de fondo de la nebulosa. Observaciones espectroscópicas realizadas desde la tierra indican que muchos de esos objetos, denominados "*proplyds*", están asociados con chorros de gas altamente supersónicos que pueden estar generando los choques que se observan.

ABSTRACT

The Hubble Space Telescope has begun to play an important role in understanding the process of star formation in the vicinity of the Orion Nebula. Recent images in the northern region reveal the previously known Herbig-Haro objects to be highly irregular in form and displaced from the infrared images, providing a promise of the ability to build unique models for those objects. The high resolution also will offer the chance to measure the expansion motions precisely. In the southern part of the nebula we see HH 203 and 204 in unprecedented detail and have discovered numerous blue shifted high ionization shocks. The most remarkable discovery has been that a majority of the low mass pre-main sequence stars have circumstellar material rendered visible either through the outer portions being photoionized and/or the obscuration of the background light from the nebula. Groundbased spectroscopy indicates that many of these objects, called proplyds, have associated highly supersonic jets which can account for producing the shocks that are seen.

Key words: **ISM: HII REGIONS — ISM: JETS AND OUTFLOWS — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

The region of the Orion Nebula (M42, NGC 1976) deserves special attention by those interested in young stellar objects and their associated phenomenon. At 440 pc the region is reasonably close (Herbig & Terndrup 1986). Moreover, it is very rich, with total star densities approaching 10^5 pc^{-3} (Herbig 1982, Prosser et al.

1994) and the star cluster associated with the early type stars of the Trapezium Cluster have a well defined age range of 300,000-2 $\times$ 10^6 years (Prosser et al. 1994). The difficulty in study of this region is presence of the radiation from nebula, which is caused by the photoionization from the hottest stars; however, we shall see that this process can also be turned to advantage in the detection of circumstellar material around the low mass young stars.

The structure of the nebula is now understood in three dimensions. Wen & O'Dell (1995) have developed a physical relation expected to exist between the surface brightness of the nebula in Hα and the distance from the dominant ionizing star (Baldwin et al. 1991) to build a three dimensional model of the ionized material. The nebula is actually a thin blister of ionized gas (Wurm 1961, Zuckerman 1973) on the near side of the giant molecular cloud OMC-1. The gas density drops rapidly away from the ionization front marking the boundary with OMC-1 and the emissivity drops to e^{-1} in a distance corresponding to an angular size of about 10$''$. The ionization front is highly irregular, rising towards the observer to the southwest from the Trapezium and rolling upwards in an escarpment to the southeast which produces the nearly linear feature know as the Bright Bar. In the foreground and at a distance several times the separation of the Trapezium stars and the main ionization front lies a neutral lid of material which is marginally optically thin in the visual window (O'Dell et al. 1992). The Trapezium Cluster of stars lies between this thin lid in the foreground and the main ionization front in the background.

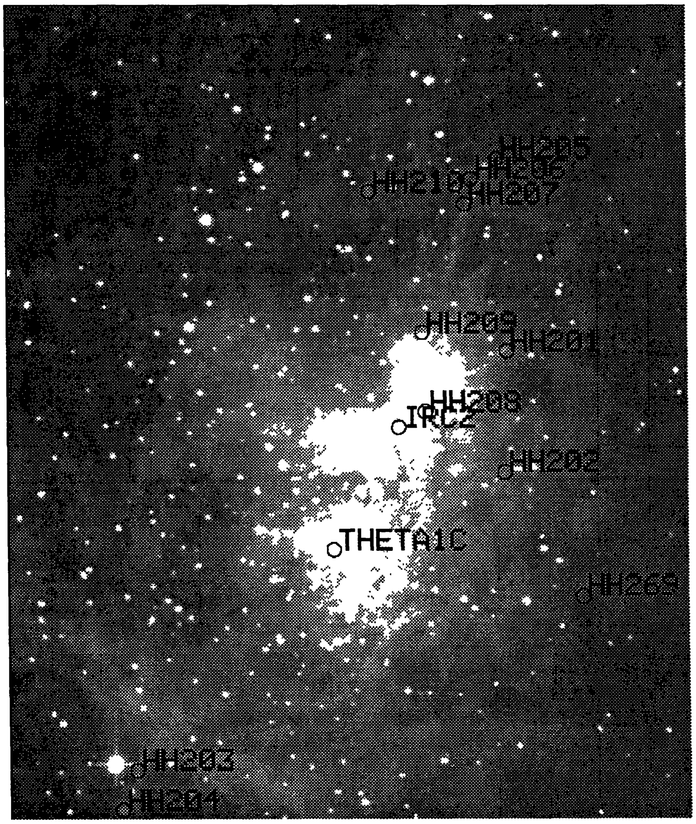

Fig. 1.— A combined H_2+[FeII] infrared image of M 42 (from data of Allen & Burton 1993) with the position of the eleven designated HH objects shown in addition to that of IRc2 and θ^1C Ori. North is at the top in all images of this article

The infrared and radio picture of this region is quite different (Genzel & Stutzki 1989). At these longer wavelengths one can see into OMC-1 and one finds that there is another HII region centered about the source IRc2. The three dimensional picture of this enclosed HII region is very uncertain, although we will present evidence in the next section that it probably does not lie deep within the neutral cloud.

2. SOURCES ASSOCIATED WITH OMC-1

Only the most luminous portions of the young star region within OMC-1 are seen in the infrared. Fortunately, these are enough to delineate the position of the activity. Radio observations show that this same zone is very active (Genzel & Stutzki 1989). There are numerous Herbig-Haro objects (HH) which seem to be associated with this region. These were originally discovered by Axon & Taylor (1984) and optical spectra indicated that they have primarily blue shifted emission most intense near the systemic velocity and with decreasing intensity out to 380 km s^{-1}. A subsequent proper motion study by Jones & Walker (1985) indicated that three of the objects (HH-201,205,210) had high proper motions (up to 11″/century), with tangential velocities headed away from the embedded source IRc2. Combining the proper motions and separations gives expansion times for these features of about 700 years.

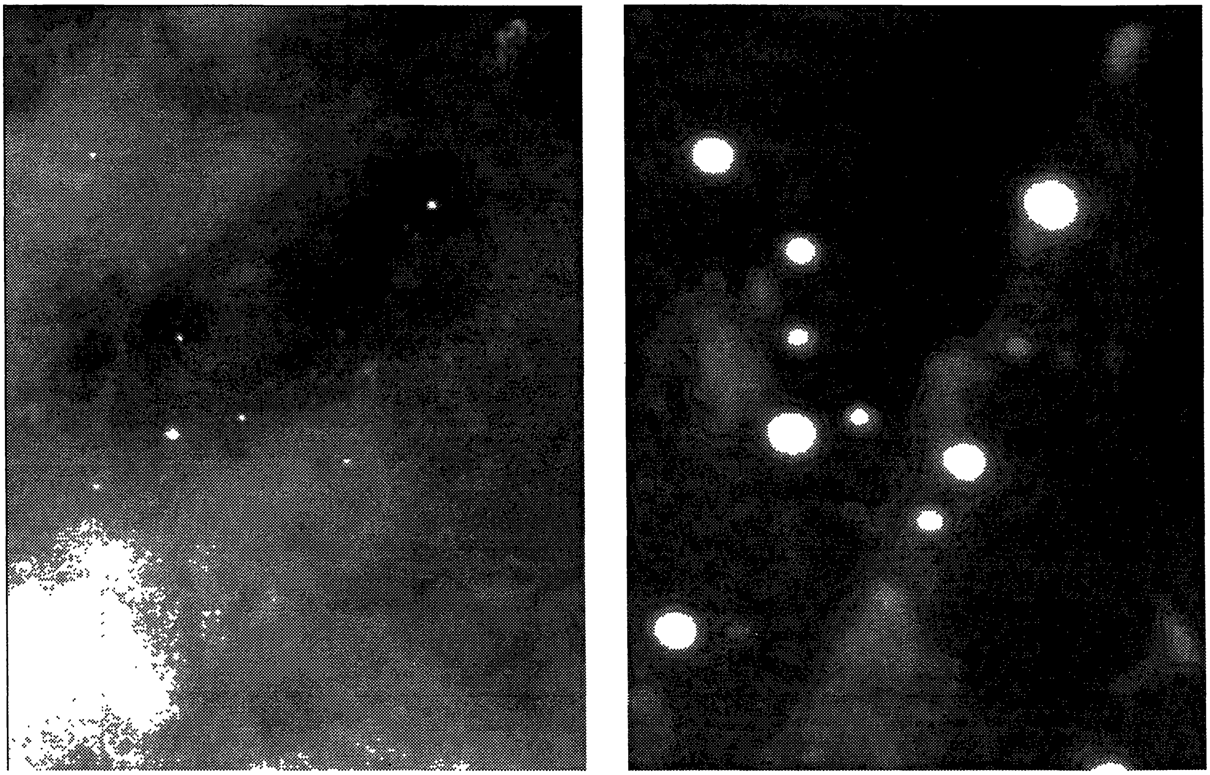

Fig. 2.— High resolution images of the vicinity of HH 205-7. The left image is a composite Hα+[NII] HST image in the low resolution portion of the field (0.10″/pixel). HH 205 is at the top right corner of the image, HH 206 in the center, and HH 207 in the low middle center. Un-named HH features lie to the immediate left of HH 206 and the left center section. The right image is a composite H_2+[FeII] image originally made at 0.25″/pixel but scaled to the same field as the HST image.

The association of most of the northern HH objects near the Orion Nebula with IRc2 was dramatically confirmed in the infrared images made in shock excited infrared emission from [FeII] and H_2 by Allen & Burton (1993). Their image is reproduced in black and white in Figure 1. This shows how there seem to be a series of radial spokes originating from a common region (IRc2). A color depiction of these images reveals how the lower excitation H_2 emission arises from further away from the tip of the apparent shocks than the [FeII] emission, while the optically visible HH objects fall at the very tip of a large fraction of the radial features. The fact that the associated HH objects are bright in the orange (they were first detected in [OI] 6300 Å) indicates that at least these portions of the features are not buried deep within the high optical depth giant molecular cloud.

A very recent Hubble Space Telescope (HST) image of the region around HH 205-7 and 10 is shown in Figure 2a with an undersampling pixel size of 0.10″ as a composite of [NII] 6583 Å and Hα emission. Figure 2b shows the same region at the same orientation and scale in a composite picture in [FeII] plus H_2 emission prepared from a digital copy of the data of Allen and Burton, the latter image being slightly oversampled at a pixel size of 0.25″. We see that the actual ends of the bow shock shaped tips break down into numerous bright knots, rather than being the expected smooth feature. Comparison with Figure 2a shows that the [FeII] emission almost coexists with the Hα and [NII] emission in spite of their very different excitation mechanisms and energies. The strong infrared source just east of HH 206 has a multicentered optical counterpart seen here for the first time. In addition, Figure 2b shows a strong source well displaced to the east from HH 206 whose northern terminus has an optical counterpart. There is a well defined dark lane extending from this feature in a direction that includes both HH 201 and 202, but not IRc2. Since HH 205 and 210 were measured by Jones and Walker on groundbased images to have proper motions that correspond to one pixel per year, it is practical to accurately determine the motion of these objects in only a few years. Moreover, the resolved structure in various emission lines will allow detailed comparison with models for these objects as bullets or shocks, a distinction difficult to make from ground data alone.

3. HH OBJECTS ASSOCIATED WITH THE TRAPEZIUM CLUSTER

There appears to be a second set of HH objects associated with the Trapezium Cluster of stars that lies on the near side of the main ionization front lying on the front of OMC-1. The best defined of these is HH 203, which appears as a nearly parabolic form, much brighter on the northeast side and having an apex pointing to PA=133°. The nearby object HH 204 is much more irregular in shape. Both are shown in a composite [NII]+Hα image in Figure 3 in another recent HST image obtained as part of the author's program to prepare a mosaic of the entire Huygens region of M 42. In this case the field lay entirely within the high resolution CCD of the WFPC2 and each pixel is 0.046″, slightly oversampling the image. This same region had previously been imaged by the HST both before (O'Dell et al. 1993) and after (O'Dell & Wen 1994) the refurbishment mission in the same filters, although the former study included only HH 203. The brightest portions of HH 203 and 204 have heliocentric radial velocities of –48 and –25 km s^{-1}. The radial velocity of the local ionization front is about 18 km s^{-1}, so that these objects are hypersonically blueshifted with respect to the ionized gas and have even higher velocity differences relative to OMC-1 which has a velocity of about 28 km s^{-1}, which agrees with that of the low mass stars of the Trapezium Cluster. The bright northeast boundary of HH 203 extends back in direction towards θ^1C Ori, but tantalizingly stops at the proplyd Orion 177-341 (O'Dell & Wen 1994) where it blends into the tail of that object, suggesting that what we are seeing there is a stream of emission from that young stellar object which terminates in a shock denoted as HH 203.

Fig. 3.— A 73″ square field around HH 203 (upper) and HH 204(lower) is shown in this composite Hα+[NII]+[OIII] HST WFPC2 high resolution (PC) image (0.046″/pixel). The bright star at the upper left is θ^2A Ori.

HH 202 is probably also associated with the Trapezium Cluster even though it lies on the opposite side of the Trapezium stars. The most detailed image of it was made in multiple emission line filters early after the HST launch (Hester et al. 1991). The object is actually two bright knots of about 1″ size, separated by about 5″ and located near the apex of a parabolic form pointing towards PA=305°, i.e. again away from the center of the Trapezium Cluster. A multiple ion spectroscopic study of the motion in this region (O'Dell et al. 1991) indicates that there are two blueshifted hemispheres (possibly shocks) at heliocentric velocities of –30 and –73 km s^{-1} and a jet starting at about –30 and going up to about –90 km s^{-1}. The object is of low ionization and does not appear in [OIII] but Meaburn (1986) has mapped an expanding shell of blue shifted [OIII] on the south side of HH 202.

There is another object that lies nearby and is probably associated with the Trapezium Cluster. Possessing many of the characteristics of an HH object, it has been assigned the number HH 269 in the sequential numbering system for HH objects of Reipurth (1994). Although apparent for some time on images of M 42, this object was first the subject of a paper by Feibelman (1976) who argued for its having a large proper motion of expansion and has recently been investigated by emission line imaging together with high and low resolution spectroscopy (Walter et al. 1995). HH 269 is a low ionization ellipse of 41″ x 23″ lying on an east-west axis with a center at $5^h32^m41.72^s$ $-5°25'38''$ (1950). It is marked by two bright knots at the east and west ends, which have heliocentric radial velocities of –13 and –24 km s^{-1} respectively. There is no associated jet, but there is some infrared evidence of a link to the nearby pre-main sequence star Jones & Walker (1988) 352 which also has the variable star designation LQ Ori.

4. THE PROPLYDS

The biggest surprise from the first set of HST images of the region south of the Trapezium (O'Dell et al. 1993) was the clear identification of a new class of objects, which have come to be called proplyds. A proplyd is defined as a young star with circumstellar material rendered visible by being visible by being in or near an HII region and the term arises as a contraction of protoplanetary disk, which is probably what many of them are. Their existence as a class was confirmed by the second, higher resolution observations with HST in this same region (O'Dell & Wen 1994). Half of the stars down to V=21 are proplyds and since it is easier to detect the star than the surrounding gas and dust, this is undoubtedly a lower limit. Why the proplyds are seen is usually through their external ionization by θ^1C Ori or θ^2A Ori, the O type stars which dominate the hydrogen photoionization process. In each case the near side of the circumstellar material is photoionized by the O star and sometimes this ionization boundary extends around the circumference of the object, the rearward ionization probably being by diffuse Lyman continuum photons. The objects are commonly distorted and those nearest θ^1C Ori are highly subtended, showing a bright cusp oriented towards the photoionizing star and possessing a tail facing away.

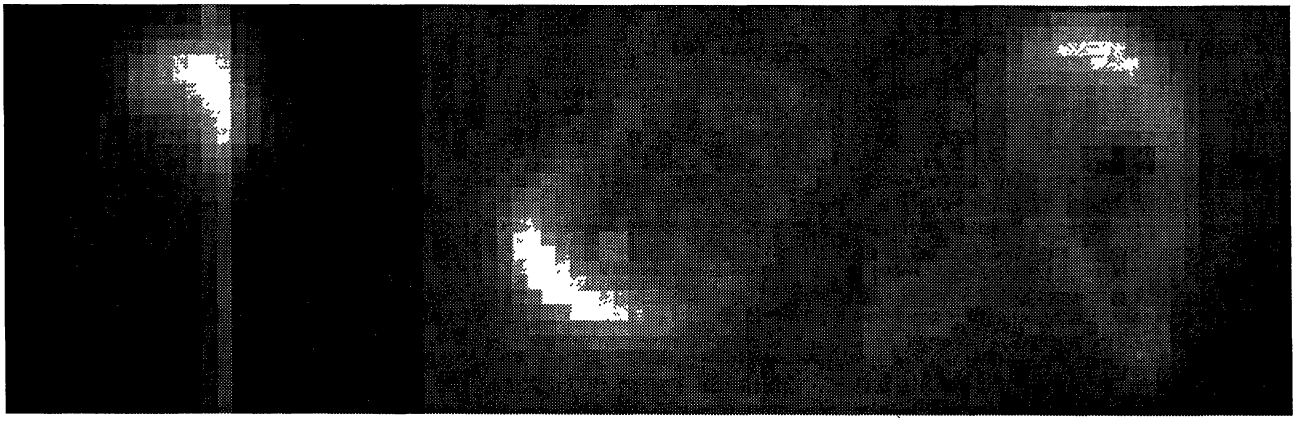

Fig. 4.— Three typical Orion proplyds which are photoionized on their outer edges. From left to right they are Orion 177-341, 206-447, and 182-413 (using the notation of O'Dell & Wen 1994). The images are each composites of Hα+[NII]+ [OIII] emission. Each field is 3″ square. The vertical streak through the left figure is a CCD readout characteristic arising from a nearby bright star.

Such objects have been detected previously. Laques & Vidal (1979) first detected six high ionization ones near the Trapezium as unresolved emission line objects which they incorrectly interpreted to be PIGS (partially ionized globules). Subsequent high resolution VLA maps of the Trapezium region yielded many additional sources as at best marginally resolved thermal ionized sources of high surface brightness (Churchwell et al. 1987, Garay et al. 1987). The correct interpretation of these objects as circumstellar material around a young

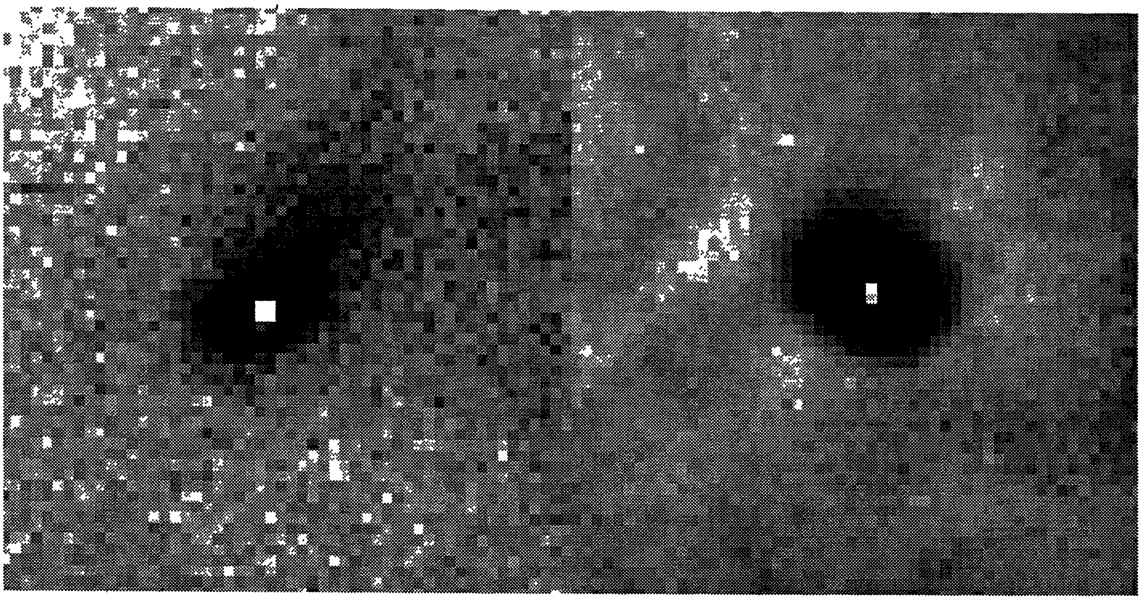

Fig. 5.— The two Orion proplyds showing only in silhouette against the background nebular emission. On the left is Orion 120-1925 and on the right is Orion 183-405. These images are composites of Hα+[NII]. These portions of the PC images are fields of 2.5″ square.

star was actually argued by Churchwell et al. and by Meaburn (1988) from the marginally detected presence of a few stars in some of the objects. It was, however, the improved resolution of the HST (even in its original degraded form) which made identification of their true nature possible.

A depiction of several of the proplyds is given in Figure 4, where we see the variety of forms well illustrated. The shaping force for the radial structure away from the nearby O star can be either the stellar wind or its radiation pressure (McCullough et al. 1995) although it is more likely to be the latter (O'Dell & Wen 1994). The ionized mass of these objects is characteristically $2x10^{28}$ gms.

There are at least two proplyds that lie sufficiently far away from the ionizing stars to not be significantly photoionized and they are depicted in Figure 5. In this case the stars are readily visible and their dust component renders the circumstellar disks visible in silhouette against the bright background nebular emission. One of these objects (Orion 183-405) has had the mass of its outer portion determined to be $0.1\text{-}4.4x10^{28}$ gms. Since the ionized mass for the photoionized proplyds would be a lower limit to the total mass of those objects, we are certainly talking about circumstellar masses that are at least 10^{-5} that of the nascent stars.

5. OTHER SHOCKS AND FLOWS

An additional surprise in the results of the first HST images of the region south of the Trapezium was the large numbers of shock features (O'Dell et al. 1993). These take the form of a large number of high ionization (strong [OIII] emission) arcs of varied radius and thickness. These seem to be centered on the region of highest concentration of the low mass stars, which occurs to the south of the Trapezium. That they are shocks is confirmed by spectroscopy of that region. Slit spectra indicate small regions of highly blue shifted [OIII] emission at –20 to –40 km s^{-1} (Castañeda 1988, O'Dell et al. 1993) and some points even up to –104 km s^{-1}(Lee 1969). In addition to these smaller features, a 1′ radius shell centered on the Trapezium and having an expansion velocity of –100 km s^{-1} was seen by Meaburn et al. (1993).

In addition to these resolved shocks, there is another type of high velocity system seen most clearly in [OIII]. John Meaburn of Manchester University has mapped the near Trapezium region in the 5007 Å line at progressively higher spatial coverage and limiting brightness (Massey & Meaburn 1995, Massey & Meaburn 1993, Meaburn et al. 1993, Meaburn 1988). Meaburn and his collaborators find a myriad of jets of emission. By jets I mean emission line regions possessing a continuum of velocities from that of the ambient gas to high values. Characteristically these jets are blue shifted and extend to about –100 km s^{-1} although some red shifted components are also seen. These jets seem to correspond in position to the brightest proplyds and Meaburn argues that they represent collimated outflows from these young stellar objects, which is certainly consistent with their pre-main sequence state. These jets are also seen in lower ionization lines and are the subject of an extended investigation of flows in this region (Hu 1995).

6. CONCLUSIONS

The Orion Nebula has begun to reveal its characteristics as a rich region of recent star formation. Two subregions exist, one within OMC-1, the other in the ionized material near the Trapezium stars. The former subregion is seen in HST images as a system of HH objects apparently originating from the imbedded source IRc2. The latter subregion is seen in a number of ways. Most of the low mass pre-main sequence stars are proplyds, i. e. young stars surrounded by circumstellar material rendered visible by being in or near an HII region. These proplyds seem to be the sources of collimated outflows which are seen spectroscopically near the objects and give rise to bow shocks throughout the inner Orion Nebula. The author is conducting a survey of the population of the entire inner region of M 42 using the WFPC2 of the HST.

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