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Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
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OUTFLOWS, JETS AND SHOCKS IN THE ORION NEBULA

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RESUMEN

El cúmulo de estrellas jóvenes asociadas a la Nebulosa de Orión es un buen laboratorio para el estudio de los plasmas. Vemos cinco tipos de flujos y choques. Los flujos de foto-ablación de los proplyds más cercanos a θ^1Ori C forman choques cuasi estacionarios con el viento de la estrella. Se observan micro-chorros con escalas menores a 10^3 AU en 20 estrellas pequeñas. Los chorros aislados, con altas velocidades y escalas cercanas a 10^4 AU, son comunes pero menos numerosos. También se ven choques cuando los chorros golpean al gas nebular ionizado o al gas neutro del fondo. El tipo de objeto final es el choque estacionario formado por la interacción del viento estelar, generado durante la formación del disco, con el gas ambiental que fluye hacia afuera de la nebulosa.

ABSTRACT

The rich young cluster of stars associated with the Orion Nebula provides a unique laboratory for the study of plasma phenomena. We see five types of flows and shocks. Photoablation outflow from the proplyds nearest θ^1Ori C form nearly stationary shocks with the high velocity wind from that star. Microjets, with scales of less than 10^3 AU, are seen around some 20 low mass stars. Isolated jets, with high velocities and scales of about 10^4 AU, are less numerous but common. One also sees the shocks formed when these jets impinge on the ionized nebular gas and the neutral gas in the foreground lid. The final type of object is the stationary shock formed by the interaction from the stellar wind that arises during disk formation with the ambient gas flowing away from the main body of the nebula.

Key Words: **CIRCUMSTELLAR MATTER — ISM: INDIVIDUAL (ORION NEBULA) — ISM: JETS AND OUTFLOWS — STARS: FORMATION — STARS: WINDS, OUTFLOWS**

1. INTRODUCTION TO THE ORION NEBULA COMPLEX

The Orion Nebula complex offers a particular opportunity for the study of plasma phenomena. The nebula is actually a relatively thin layer of emission arising from a thin blister of ionized material on the front of a giant molecular cloud. The density of gas drops from its peak value in the ionization front (IF) with an approximately exponential density scale height of about 0.05 pc (corresponding to an angle of 26″), which means that the emissivity drops with a scale height of only 0.025 pc. The dominant source of ionization is θ^1Ori C, which lies about 0.25 pc in front of the IF. This means that the Orion Nebula Cluster of young stars, many having circumstellar clouds, is bathed in a flux of ionizing photons. In the foreground there is a lid of neutral gas and dust, beginning at about 0.7 pc from θ^1Ori C. The presence of these circumstellar clouds in an H II region makes their conditions for observation much easier and their physics much more complex. Because of their special conditions, they are given a specific name, the proplyds. The proplyds irradiated by ionizing

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photons from θ^1Ori C have their own IF facing the star, while those within or beyond the foreground lid are entirely neutral and are seen only in silhouette against the background nebula. As we shall see, the proplyds give rise to a variety of plasma phenomena, described in the next section. The results we present here are described in detail in a recently submitted paper (Bally, O'Dell, & McCaughrean 1999).

2. PLASMA PHENOMENA IN THE ORION NEBULA COMPLEX

There are five types of plasma phenomena that we wish to describe in this brief paper. They represent a wide variety of characteristics, but have the common features of being driven by the conditions of outflow from the proplyds and the conditions of photoionization by θ^1Ori C.

The first phenomena are the fronts formed when photoablating material at the local IF of the proplyds close to θ^1Ori C forms a shock with the high velocity wind arising from that star. The details of these are discussed by García-Arredondo, Arthur, & Henney in these proceedings. As one would expect, these shocks are high ionization, being best defined in [O III] emission and are stationary within the measurement uncertainties of two epoch HST WFPC2 images (about 30 km s^{-1}). They are illustrated in Figure 1*a*, with few being found at greater apparent distances from θ^1Ori C, presumably because of diminution of the stellar wind and the photoablation rate.

The second phenomena are the microjets found emanating from 20 of the proplyds. Characteristically these are about 500 AU in length and extend in to the image of the central star. Most are quite low ionization, with 244–440's microjet appearing only in [O I], as shown in Figure 1*b*. In contrast, in the proplyd 170–337 which is close to θ^1Ori C, the microjet is most visible in [O III]. Keck HIRES spectra are available of these two proplyd's microjets and blue shifted velocities of 110 and 150 km s^{-1} are found. Usually only a onesided microjet is seen, although there are several examples of bipolar jets. The preferential appearance of only one side of what must be general bipolar structure is probably due to obscuration by the inclined disk.

The third phenomena are the isolated jets, which have dimensions of about 10^4 AU. Figure 2*a* shows a good example. In this case we have both HIRES spectra and two epoch WFPC2 images. These yield values of $V_T = 85 \pm 24$ km s^{-1} and $V - R = -45 \pm 2$ km s^{-1}, meaning that the jet is coming towards the observer at an oblique angle. The jet illustrated is like the others in that it has no obvious parent star connection, probably because it is part of the grouping of stars lying within the photodissociated region behind the main IF and near the strong IR source Orion-S. Other isolated jets probably arise from optically visible stars, but the exact association cannot be made because of the combination of imprecise determination of their axes and the numerous stars in the central portion of the cluster. Some jets are only seen in contrast with the bright nebular background when high velocity components can be isolated, as in the Fabry-Perot study of the entire Huygens region by O'Dell et al. (1997a).

The fourth phenomena are the jet driven shocks. In the case where these shocks arise in the main cavity surrounding θ^1Ori C, where the low density nebular gas is already photoionized, the shocks are high ionization and best seen in [O III]. In the case of those shocks associated with HH 529 (Fig. 2*b*), the spatial velocities are about 150 km s^{-1}. The best known members of this class are the pair of shocks HH 203+204. Again, we have both radial and tangential velocities, which give spatial velocities of 86±15 km s^{-1}, 36° out of the plane of the sky and towards the observer (HH 203) and HH 204 is moving 92±8 km s^{-1}, 53° out of the plane, towards us. This pair of objects both show only low ionization lines in the shock itself, but the enclosed envelope has extended [O III] emission. O'Dell et al. (1997b) interpret this to mean that HH 203+204 are due to blueshifted jets impinging material in the foreground neutral lid.

The fifth phenomena are the low ionization shocks found around stars at the edge of the Huygens region, where the the photoablation rates must be low and the θ^1Ori C stellar wind highly diluted. The most visible example is the shock around the T Tauri star LL Ori (Figure 3), although there are nine others. These are stationary within the limits of the accuracy of the tangential velocities. We interpret these to be the results of shocks forming by the collision of the outflow wind that accompanies low mass star formation with the moving ambient gas. The strongest support for this interpretation is the fact 114–426 has such an associated shock. 114–426 is the largest of the silhouette proplyds. Since it has no local IF there can be no photoablation, so that its outflow wind must be associated with the existence of the circumstellar disk.

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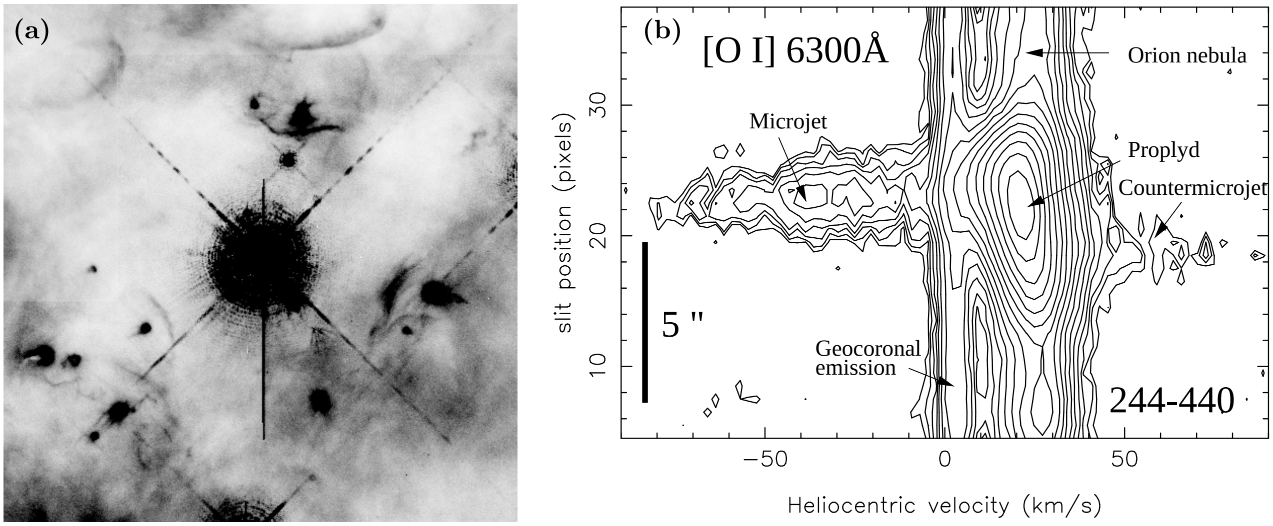

Fig. 1. *(a)* A 23″ square region around θ^1Ori C is shown in [O III] in this HST WFPC2 image. Multiple proplyd photoablation-stellar wind shocks are seen in negative depiction. *(b)* A Keck I HIRES slit spectrum across the proplyd 244–440 is shown. The strong nebular emission near 25 km s^{-1} dominates the spectrum, although at the proplyd's position emission near the same velocity is seen near $y = 22$. The strong blueshifted microjet emission and fainter redshifted counterjet emission occurs near the same y values.

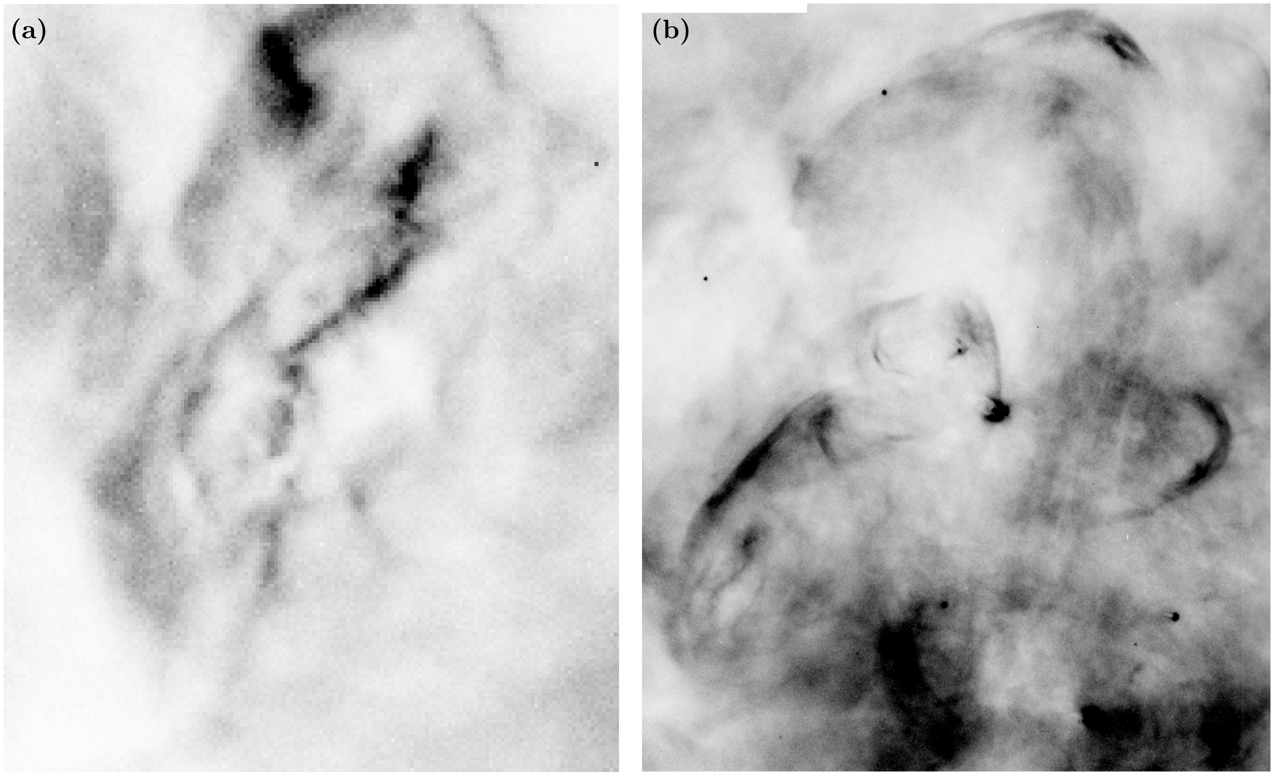

Fig. 2. *(a)* Hα negative image of a 7.6 × 9.3″ field around the isolated jet associated with HH 529 (Reipurth 1999) that originates from the near the Orion-S molecular source. *(b)* [O III] negative image of a 20 × 25″ field centered on proplyd 159–350 and manifests multiple high ionization shocks driven by the left hand jet and similar collimated stellar outflows.

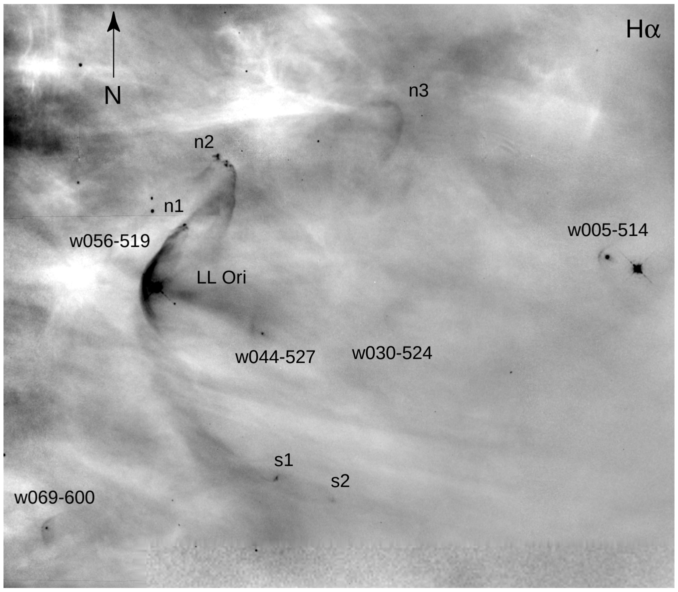

Fig. 3. A $115 \times 100''$ region around the T Tauri star LL Ori is shown in this Hα WFPC2 negative image. The star is barely visible near the inner side of the bright shock to the left. Several examples of nearly stationary cool star wind shocks are seen, each labeled with a name starting with the letter w. The n1, n2, and n3 features are high velocity shocks that would normally be interpreted as being driven by a jet outflow from LL Ori. The similar structures (s1 and s2) to the south (which have no measured motions) argue that there may be a more complex interpretation.

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