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STRUCTURE, MOTION, AND COMPOSITION OF THE ORION NEBULA

C. R. O'Dell
Department of Space Physics and Astronomy, Rice University

RESUMEN

Presento una revisión de la estructura a gran escala de la Nebulosa de Orión, incorporando resultados recientes de estudios de absorción en 21 cm, investigaciones de líneas ópticas de emisión e imágenes del Telescopio Espacial Hubble. La estructura de ionización en el frente de ionización más brillante está claramente definida y demuestra un flujo bien organizado que se aleja del frente. La parte ionizada se mueve rápidamente hacia la Nube Molecular de Orión y las nuevas imágenes revelan estrellas de baja masa formadas recientemente y rodeadas de discos protoplanetarios.

ABSTRACT

I review the large scale structure of the Orion Nebula, incorporating recent results from 21 cm absorption studies, optical emission line investigations, and Hubble Space Telescope imaging. The ionization structure at the brightest ionization front is clearly defined and demonstrates a well organized flow away from the front. The ionized portion is moving rapidly into the Orion Molecular Cloud and the new images reveal recently formed low mass stars surrounded by protoplanetary disks.

Key words: **ACCRETION, ACCRETION DISKS — H II REGIONS — STARS: FORMATION**

1. BASIC STRUCTURE OF THE ORION NEBULA

In spite of its optical brightness and proximity, the Orion Nebula (M42, NGC 1976) has only recently begun to yield accurate information about its physical structure. Certainly most of the emission comes from a principal ionization front as originally envisioned by Wurm (1961), advanced again convincingly by Pankonin et al. (1979), and most recently advocated by O'Dell & Wen (1992). Lying on the far side of the dominant ionization source ($\theta^1 C$ Ori), an ionization front is the interface between the HII region we observe optically, and the molecular cloud OMC-1, which is accessible only to radio and infrared observers.

The distance of the ionization front from the star can be determined from the fact that as viewed from the ionizing star the total number of ionizations in a column must be equal to the total number of recombinations, which in turn is proportional to the surface brightness. Originally stated in its simplest form by Baldwin et al. (1991), this method leads to a stellar separation distance of 0.2-0.3 pc, depending upon whether the total number of HI ionizing photons from $\theta^1 C$ Ori is 1 or 2×10^{49} photons per second. Similarly, one can use the reflection of the Trapezium optical continuum to set the distance at 0.4 ± 0.2 pc. The agreement of these very different methods implies that we have a good idea of the value of this fundamental number for modeling the nebula. For reference, Baldwin et al. (1991) derive a value of the central region HII emission zone thickness of 0.1 pc.

However, M42 is overlain with a mixture of dust and gas. The HI 21 cm absorption line studies of van der Werf & Goss (1989, 1990) have established clearly the presence of a three velocity component layer of neutral material lying between the observer and the nebula. A more recent study (O'Dell et al. 1993a) shows from a correlation analysis that most of the optical extinction occurs in this same neutral cover. In an attempt to clarify the structure of this "lid", O'Dell et al. (1993b) determined the velocities and column densities of HeI, NaI, and CaII in the four central Trapezium stars and the nearby star $\theta^2 A$ Ori. They found that heavy elements in the lid produced absorptions and that there were multiple additional absorbing systems, most of which are probably in the foreground, although the velocities are anomalously high. The presence of the neutral lid means that there will be at least one additional ionization front, which may have been detected in the [OII] emission line study of Jones (1992).

A new mechanism affecting what is observed in emission line studies was revealed by analysis of the velocity profiles of [OII] (Jones 1992), [OIII] (Castañeda 1988), and [SIII] (Wen & O'Dell 1993). Although it is well known that the stellar continuum from the Trapezium is scattered by dust, in fact it swamps the nebular atomic continuum, we had not thought about the inevitable scattering of the emission lines by the dust. Examination of the high resolution emission line spectra reveals that there is a scattered light component, which is red shifted from the principal emission and significantly broader. The reflection occurs near the ionization front, which has a more positive velocity than where the emission occurs. The reflecting layer essentially acts as a moving mirror, doubling the velocity difference and broadening the lines as any one reflecting point is illuminated from a variety of angles and hence different relative velocities. A comparison of the extinction corrected HII optical surface brightness with the 21 cm continuum radio emission came to the same conclusions, i.e. that significant reflection of the optical emission occurs (O'Dell et al. 1993a). The efficiency of this reflection has not yet been determined exactly, is probably about 0.4, but needs to be determined, as many calculations of nebular conditions assume isotropic emission and free escape.

Although modeling of the Orion Nebula is a vigorous theoretical activity (Rubin et al. 1991, Baldwin et al. 1991), the basic ionization structure can be understood from only a few theoretical considerations, examination of a few high quality emission line images, and study of the emission line ratios. Because of their large abundances, the energy dependent opacity of the ultraviolet continuum is primarily determined by HI, HeI, and HeII. This means that the ionization potentials of various heavy elements cause their various stages of ionization to be found in particular stratification zones determined by HI, HeI, and HeII. Since the brightest optical heavy element lines are collisionally excited forbidden lines, then the zones of emission can be prescribed even further. Hester (1991) has pointed out that the [SII] emission can arise only from the ionization front itself, a property shared by the [OI] emission. In the zone where hydrogen is ionized but helium is neutral, one would expect to find emission arising from [SIII], [NII], and [OII]. Closer to the ionizing star, one would find the helium to be singly ionized and find emission from recombinations to HeI and also [OIII]; the higher ionization states of sulphur and nitrogen not being observable in the optical. Theoretically, a zone of doubly ionized helium could exist, but does not in M42 since no recombination HeII is detected.

We can test this basic approach to modeling M42 by examining certain line ratios and then use other line ratios to determine the size of the various ionization zones. First we can consider the ionization front itself, which should have a width of only 10^{-4} pc (corresponding to an angle of 0.04" at a distance of 500 pc). Since the [SII] and [OI] emission can only come from this region, we can calculate the expected relative flux ratios of the combined [SII] 671.7+673.1 nm doublet to the [OI] 630 nm line. Using the atomic parameters of Osterbrock (1989) and Aller (1984), the abundances in Osterbrock (1989) of N(S)/N(O)=0.046, and an electron temperature of 9,200 K predicts a flux ratio of F([SII])/F([OI])=3.9 when collisional de-excitation can be ignored. The observed values of Baldwin et al. (1991) are very close to this value away from the center of the nebula, but drop to about 2.0 near the high density center. This drop is clearly attributable to collisional de-excitation of [SII], which has a critical density of about 8,000 electrons/cm^3 while the [OI] critical density is 1.8×10^6 electrons/cm^3 and the central densities are well known to be about 10^4(Pogge et al. 1992).

The next zone, where hydrogen is ionized but helium is still neutral, can be characterized by comparing the [NII] 658.4 nm line with the combined [SII] doublet. Again using Osterbrock and Aller's values and an abundance ratio of N(N)/N(S)=2.2, gives for the ratio of volume emissivities j([NII])/j([SII])=0.3, if all of the elements are in the observed ionic states. The observed ratios of Baldwin et al. (1991) vary from as large as 9.2 to 2.5. This means that the neutral helium zone is only about 8 to 30 times as wide as the ionization front, and corresponds to distances of 0.8-3 $\times 10^{-3}$ pc and angles of 0.3-1.2" This would argue that the neutral helium zone is very thin as compared with the 0.1 pc found for the total HII emission zone by Baldwin et al. (1991). This result agrees with the best images of M42, obtained with the Hubble Space Telescope (O'Dell et al. 1993) where the [OI] and [SII] boundary is less than the resolution (FWHM =0.18", corresponding to 4×10^{-4} pc) and the [NII] emission is almost equally sharp when looking at regions along the ionization front, such as found along the bright bar southeast of the Trapezium.

2. MOTION OF THE ORION NEBULA

Fine scale motions within Orion have been the subject of several studies at Rice University over the last decade, extending the pioneering observational work of Wilson et al. (1959) and interpretations of Munch (1958). Working at resolutions finer than the thermal broadening of the lines, the results of Castañeda (1988) characterized the main [OIII] zone, while the neutral helium zone was studied through [OII] (Jones 1992) and [SIII] (Wen & O'Dell 1993), and the ionization front itself was measured through [OI] (O'Dell & Wen 1992). A more recent and less complete study (O'Dell 1993, Wen 1993) has extended this work to HII, HeI, [SII], and [NII].

The gross velocity structure of the main ionization front is well defined. The molecular emission from the molecular cloud is at 28 km/s, as determined by CO (Goudis 1982), as is the CII radio recombination emission which must arise on the neutral cloud side of the ionization front. The ionization front, seen in [OI] and [SII] is at 25.5±1.1 km/s. The neutral helium zone, seen in [NII], [OII], and [SIII], is at 18.8±1.5 km/s. The high ionization zone, seen in HeI and [OIII], is at 17.9±1.3 km/s. The HII emission, which arises from all of the zones, especially the much larger high ionization zone, is at 16.0±1.2 km/s. Since the HII recombination process is weighted towards lower electron temperatures, the region sampled by the HII emission may be slightly different from the rest.

A very self consistent picture arises from this data. The molecular cloud is at 28 km/s, and material is flowing out from it through the ionization front at 25 km/s. The material then rapidly accelerates further, reaching 18 km/s for the parts closest to the cloud and 16 km/s further away. The reflection data give similar results, with the reflection of the emission from the [SII] from the ionization front occurring at 28±2 km/s, and the reflection from the main emission occurring at 20 km/s.

The motion of the ionizing star is an important consideration in understanding both the structure and evolution of M42. The proper motion of $\theta^1 C$ Ori has been determined by van Altena et al. (1988) to be towards PA= 142° at a rate of 2.3 mas/yr, corresponding to a tangential motion of 5.4 km/s. Probably more important is the radial velocity, which is given in the Bright Star Catalog (Hoffleit 1964) to be 33 km/s, which means that $\theta^1 C$ Ori is moving into the molecular cloud at 5 km/s. This motion is very important since it probably drives the rate of motion of the ionization front. In fact, if one takes a separation distance of the star and the current ionization front as 0.25 pc, then the time for the star to move to that position is only 50,000 years, which is vastly shorter than the age of the star and longer than the recombination timescale for the nebular material, i.e., the star will be around for long enough and the gas responds quickly enough that the structure can be significantly altered by the star's motion. Not only is the radial velocity important, it is also uncertain. At spectral type O6, all of the lines are weak and diffuse, with the HeII lines being blended with the Balmer HI lines. It would be very important to determine this velocity accurately.

3. NEWLY DISCOVERED OBJECTS

Recent Hubble Space Telescope (HST) images (O'Dell et al. 1993c) have clarified the nature and number of a new type of object in M42. Basically this is something that we should have been looking for all along. We knew that Orion is a region of recent star formation and that star formation is almost certainly accompanied by the creation of disks of material which contain most of the initial angular momentum of the prestellar cloud. Likewise, we know from the study of Herbig-Haro objects that they are most likely to be shock fronts formed by the interaction with the ambient material of jets coming out of newly formed star-disk systems. What we have found is what we should have sought. When these protoplanetary disks are caught up by the main region of ionization by the passage of the moving ionization front, their outer parts will become ionized and gas will begin flowing away from them, rendering them easily visible, especially where this outward flowing gas shocks the ambient nebular gas and where this gas is shocked by the intense stellar wind coming from $\theta^1 C$ Ori. There dust component may be rendered visible by obscuring the background nebular emission from the main ionization front.

The first such objects were discovered by Laques & Vidal (1979) near the Trapezium, and more than twenty additional ones were found by high resolution VLA studies (Garay et al. 1991, Churchwell et al. 1991). Our HST images reveal all of the point radio sources to have optical counterparts, many of them resolved into dark disks surrounded by shocked gas and having pre-main sequence central stars. We call these objects by a separate name, proplyds, because they are a distinct class of objects, star-disk systems rendered easily visible through their presence in or near an HII region. In addition, these HST images also show that there are numerous shocks across the brightest parts of M42 (where the proplyds are concentrated), indicating interactions with the jets that probably accompany the star-disk systems.

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C.R. O'Dell: Rice University, Space Physics & Astronomy Dept., P.O. Box 1892, Houston, TX 77251-1892, U.S.A.