NASA

Technical Memorandum 79666

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(NASA-TM-79666) DISCOVERY OF TWO DISTORTED INTERSTELLAR BUBBLES (NASA) 20 p HC A02/MF A01 CSCL 03A

N79-23853

Unclas

G3/89 25912

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NOVEMBER 1978

National Aeronautics and
Space Administration

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DISCOVERY OF TWO DISTORTED INTERSTELLAR BUBBLES

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ABSTRACT

During an extensive program of direct imagery of emission nebulae, arcuate structures have been found around two stars. A well-defined shock-like structure is found about the T-Orionis variable LL Orionis, located to the side of the Orion Nebula. A less extensive shock-like structure is also found about the runaway star ζ Ophiuchus. These structures can best be described in terms of distorted interstellar bubbles. A direct consequence of this interpretation is an independent estimate of the rates of mass loss for these stars.

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I. INTRODUCTION

During the past five years one of the authors, T. Gull, has been carrying out an extensive study of galactic emission nebulae using direct imagery through narrow passband interference filters. Bright emission lines characteristically emitted by a variety of emission nebulae, and selected regions of the continuum, are well isolated by the filters used in this study. Selected bright H II regions were observed using the prime focus cameras of both the KPNO and Cerro Tololo 4-meter telescopes. Passbands isolating Hα + [N II], [S II], [O III] and continuum were used to record the brightest portions of these nebulae with a few arcseconds resolution. A complete, sky-background limited survey in light of Hα + [N II], [S II], [O III], Hβ and continuum has been made encompassing the galactic plane between the latitudes $+7^{o}$ and -7^{o} and emission nebulae of special interest located beyond the plane. This is being published shortly as a NASA Special Publication by Parker, Gull and Kirshner (1979). From a preliminary examination of all of this material, we noted two unusual well-defined arcuate structures centered upon remarkably dissimilar stars. In Section II, we shall gather all of the observational material relating to these objects. We give an interpretation of their physical nature in Section III, and Section IV contains a discussion regarding what can be learned from these distorted interstellar bubbles.

II. OBSERVATIONS

a. Direct Imagery

Direct imagery through interference filters is proving to reveal many new and intriguing emission line structures both of new emission nebulae and within known, classical nebulae. For example, the galactic plane survey has detected several new emission nebulae, most notably a 3 x 4 degree supernova remnant in Cygnus (Gull, Kirshner and Parker, 1977). The doubly-ionized oxygen in the Orion Nebula is diffuse and concentrated near $\theta 1$ Orionis while the singly ionized sulphur structure is defining the ionization boundary near the dark cloud (Gull, 1974). Rejection of the diffuse continuum and hydrogen emission reveals hither-to unexpected substructures accentuated by the forbidden line emission. These substructures include Herbig-Haro Objects, ionization bound zones and an arcuate structure.

The arcuate structure about LL Orionis has been recorded in countless photographs. However, it has only recently been noted as a consequence of the present study. In Figure 1 we present the Hβ imagery of the Orion Nebula which best reveals the characteristics of the structure around LL Orionis. Reproduction of the entire structure as seen on the original plates is most difficult because of the rapidly changing nebular background. The figure indeed shows the most salient aspects. Namely, the arcuate structure is symmetrical about an axis pointing toward the brighter portion of the Orion Nebula, and roughly parabolic in shape. It is discernible that the arcuate structure is displaced slightly (about 3") from the stellar image of LL Orionis. Moreover, there is a wake following the star. Examination of the original plate shows that the arcuate structure can be traced up to five arcminutes away from the head of the arc. It becomes progressively more diffuse until the contrast becomes too low to be visible. The most obvious characteristics of this structure are shown in Figure 2.

The arcuate structure while most visible in Hβ, is also easily seen in light of [S II] (6717Å), [O II] (3727Å), and [N II] (6584Å). The structure is visible in [O III] (5007Å), He I (5875Å), Hα (6563Å), but is noticeably more diffuse and has much less contrast because of the very bright nebular background. In fact, the head of arc can be noted in a red continuum 90Å wide passband centered at 6470Å.

Independent confirmatiom of the arcuate structure was recorded using narrower passband interference filters with an image intensifier on the KPNO #1-92 cm telescope. Perhaps the most widely distributed example of the structure is the Lick three color photograph which has appeared as the front cover on both Scientific American (October 1974 issue) and Physics Today (March 1973).

The arcuate structure noticed about ζ Ophiuchus has been seen most readily in the light of [O III] (Figure 3). However, it is faintly visible in the light of Hα + [N II]. The imagery was recorded using the galactic plane survey instrument, which is a Nikkon ED 300mm f/2.8 camera lens and two-stage image intensifier. Details of the instrument are being published with the survey (Parker, Gull and Kirshner, 1979). This instrument achieves sky-background limited imagery of [O III] through a 28Å wide filter in twenty minutes. However, the angular resolution is about one/half arcminute over a seven degree field-of-view.

It would seem astonishing that the 3/4 degree long structure in [O III] (about three parsecs at the distance of ζ Ophiuchus) has not been noted before despite numerous observations of the ζ Ophiuchus region. However, the Palomar Sky Survey does not record the structure because the photographic emulsion used for the blue survey does not respond to 5000Å. The nebulosity is so faint in [O III] that only a narrow filter passband is sufficient to reject the continuum, and a very fast optical system is needed to record the low surface brightness. The sensitivity of the image-intensified 300mm survey instrument is perhaps fully appreciated by noting that the equivalent 4-meter prime focus exposure is estimated to be twenty-four hours!

The structure about ζ Ophiuchus is also symmetrical, but much less curved compared to the LL Orionis structure. The leading edge is separated from the stellar image by about five arcminutes. Upper limits to the [S II] and blue (4215Å) continuum structure are three times fainter than the detected [O III] structure. The Hα + [N II] structure is at least two times fainter than the [O III] structure.

b. Spectroscopy

At present, spectroscopic information exists only for the LL Orionis structure. Measures of the [S II] (6717Å, 6731Å) doublet ratio and the [O III] (3726Å, 3729Å) doublet ratio indicate the nebular density in the vicinity of the arc head to be about $10^3 cm^{-3}$. With several arcseconds angular resolution, there is no strong emission detected from the arc. This is due to the low surface brightness of the arc compared to the background nebula, and also that the thickness of the arc is below an arcsecond; hence, the structure is smeared out by spectroscopic observations even with the Cassegrain spectrograph on the KPNO 4-meter telescope. Moreover, no high velocity structure along the line of sight is noted in echellograms recorded using the Cassegrain echelle spectrograph on the KPNO 4-meter telescope. This is very different from two other classes of shocked phenomena, namely, Herbig-Haro Objects and structure near θ2 Orionis also present in the Orion Nebula.

Spectra of LL Orionis show that Hα is in broad, complex emission signifying mass loss. Furthermore, the Hα profile was found to change within a three day interval. Structure of the line is noticeable from -400 km/sec to +600 km/sec. Hence the terminal velocity of this star is at least 600 km/sec.

c. Other Related Observations

The star LL Orionis has been classified (Parenago, 1964) to be a T Orionis bariable with a K0:e spectral class. ζ Ophiuchus is an O9.5V star (Lesh, 1968). LL Orionis has a proper motion μ = 0.0033 arcsec/year (Fallon, 1979) which at 500 parsecs corresponds to a $v_T \simeq 8$ km/sec. No radial velocity information is known as far as we know. ζ Ophiuchus is a well-known runaway star (Blaauw, 1961), and it is an FK4 catalog star. The value of μ is 0.0252 arcsec/year which at 180 parsecs distance corresponds to v_T = 21.5 km/sec. The published radial velocity (Blaauw, 1961; Morton, 1976) is -19 km/sec. This results in a space velocity of 28.7 km/sec. The net velocity direction is about 44^0 with respect to the plane of the sky. The projected velocity direction in the plane is about 20^0 east of north and is indicated in Figure 3. It is noteworthy that the projected axis of symmetry of the arc is in the general direction of motion. ζ Ophiuchus is a mass-losing star with a terminal velocity as measured by Copernicus of 1350 km/sec (Morton, 1976: Snow and Morton, 1976). A detailed modeling of the Copernicus observations to yield a mass loss rate has not been performed for this star. However, a good estimate for that quantity can be made by applying a scaling law derived by Cassinelli (1978), based upon results of Abbott (1978). Cassinelli found that, $\dot{m} \propto L^{1.13}$

where L is the stellar luminosity. We can now compare our star with τ Sco, which has been modeled in detail by Lamers and Rogerson (1978), who obtained $\dot{m} = 7 \times 10^{-9}$ $M_\odot$/year. Since ζ Oph is 1.1 magnitudes brighter than τ Sco, the scaling leads to a mass loss rate of $2.2 \times 10^{-8} M_\odot$/year for ζ Oph.

A concluding statement regarding ζ Ophiuchus can be made on the emission nebula surrounding the star. Radio observations, Hα surface brightness measures and studies of the interstellar absorption lines (Herbig, 1968; Morton, 1976) lead to an electron density estimate within the H II region of $N_e \approx 3\ \text{cm}^{-3}$.

III. INTERPRETATION

a. Similarities and Differences

The most obvious similarities of these two structures are that both stars are losing mass and are surrounded by emission nebulae. It is surprising though to note that the spectral types are very different, and that while ζ Ophiuchus has a relatively large space velocity, LL Orionis does not. The sound speed for an H II region having approximately solar composition and an electron temperature 10^4K is 12 km/sec. In this regard, the space motion of ζ Ophiuchus is clearly supersonic and the existence of a shock phenomenon must be implied. By the same reasoning, it would appear that the space motion of LL Orionis is subsonic. However, the relevant velocity is the velocity with respect to the surrounding medium. It is known from independent sources (Balick, Gull and Smith 1979) that the ionized gas in the vicinity of LL Orionis is moving towards the observer at about the sound speed with respect to the dark cloud. That is interpreted to mean that the ultraviolet radiation from the expansion exciting stars, $\theta 1$ Orionis, penetrates into the dark cloud, ionizing it layer by layer and causing the ionized gas to expand towards the more rarefied surrounding space. With this interpretation in mind, the velocity should be roughly isotropic so that in all directions away from the ionization boundary the gas should be moving at the sound speed. It is particularly significant to note that the arcuate structure points not at $\theta 1$ Orionis, but at the ionizing boundary known as the Bar. This leads us to conclude that the structure in LL Orionis involves a shock.

b. Modeling of the Structures

The structures are produced by the interaction of a strong stellar wind with supersonic streming interstellar gas. A situation of this nature has been modeled by Castor, McCray and Weaver (1976) and by

Weaver et al. (1977), and it corresponds to what they described as a distorted interstellar bubble. We can first use this interpretation to compute the rate of mass loss from the stars. At the head of the cone, we are dealing with a simple shock, and at the boundary the stellar wind pressure approximately equals the ram pressure of the interstellar material:

$$\frac{\dot{m}}{4\pi r^2_{min}} \cdot v_T = \rho v^2 \qquad (1)$$

where $\dot{m}$ is the rate of mass loss in cgs units, v_T is the terminal velocity of the wind, r_{min} is the separation or distance form the star to the bow head, ρ is the total mass density of the undisturbed ionized gas and v is the relative velocity of the star with respect to the surrounding gas. For the case of LL Orionis (v = 18 km/sec, v_T = 600 km/sec, $\rho = 1.6 \times 10^{-21}$ g/cm^3, $r_{min} = 2 \times 10^{16}$ cm) the derived mass loss rate is 4×10^{17} g/sec or 6.4×10^{-9} solar masses per year. For the case of ζ Ophiuchus (v = 28 km/sec, v_T = 1350 km/sec (Morton, 1976), $\rho = 5 \times 10^{-24}$ g/km^{-3}, $r_{min} = 7 \times 10^{17}$ cm) the derived mass loss rate is 1.5×10^{18} g/sec or 2.3×10^{-8} solar mass per year.

This mass loss rate is in excellent agreement with the value of 2.2×10^{-8} $M_{\odot}$/year obtained in Section II of this paper.

The shape of the bow shock (Weaver et al., 1977) is a paraboloid of revolution whose axial cross section is given by:

$$Y(z) = \left(\frac{20 L_w}{33 \pi \rho v^2} \right)^{1/4} z^{1/2} \tag{2}$$

where L_w is the mechanical luminosity:

$$L_w = \frac{1}{2} \dot{m} v_w^2, \tag{3}$$

z is the distance along the axis of symmetry from the shock head and y(z) is the distance orthogonal to the axis of symmetry.

For the case of LL Orionis, the shape we derived from equation 2 is more closed than the observed structure.

The discrepancy can be understood in terms of either of two possibilities. First, there is a projection effect where the observed z displacement is the foreshortened true displacement:

$$z_{observed} = z \cos i \tag{4}$$

This results in the parabolic surface effectively opening up by a factor of $(\cos i)^{-1}$, where i is the inclination of the symmetry axis with respect to the plane of the sky. For example, in our case, an i of about 45^o would bring the theoretical shock into coincidence with the observed structure. Alternatively, we know that the electron density decreases from 2×10^3 cm^{-3} in the core of the nebula to $2 \times 10^1 cm^{-3}$ ten arcminutes away in the general direction past the LL Orionis region (O'Dell and Hubbard, 1964). Since ρ appears in the denominator of equation 2, a gradual decrease in electron density would also contribute to opening up the paraboloid. The effect could be wholly accounted for by a decrease in electron density by a factor of six. The truth is very likely a combination of both effects. However, in figure 2, we show the 45^o projected cone.

For ζ Ophiuchus, the radial velocity and the tangential velocity lead to an inclination angle of 40 degrees, hence, the paraboloid is foreshortened by a factor of 1.3. The resulting graph is displayed in Figure 4 along with the observed shape. We feel that the agreement is very good.

IV. CONCLUSIONS AND DISCUSSION

It appears from the above section that the observations are adequately explained in terms of the distorted interstellar bubble theory, and thus we conclude that that is indeed what we have observed. From the smoothness of shape and extent of both structures, it would appear that discontinuous condensations are not significant in these H II regions. A final conclusion is that these structures are extremely powerful tools to determine rates of mass loss from stars with quite different spectral types. The three requirements for the existence of these structures, namely, a star with a strong stellar wind moving supersonically with respect to a surrounding H II region are not terribly restrictive, and hence, there should be many of such objects in the Galaxy. The dearth of discovery can be accounted for by the nearly monochromatic emissions, the low surface brightness, extreme thinness of the structure, and superposition upon the nebular background. Keeping these limitations in mind, a well-directed search should greatly enlarge our sample, and cover mass loss from stars at various stages of evolution.

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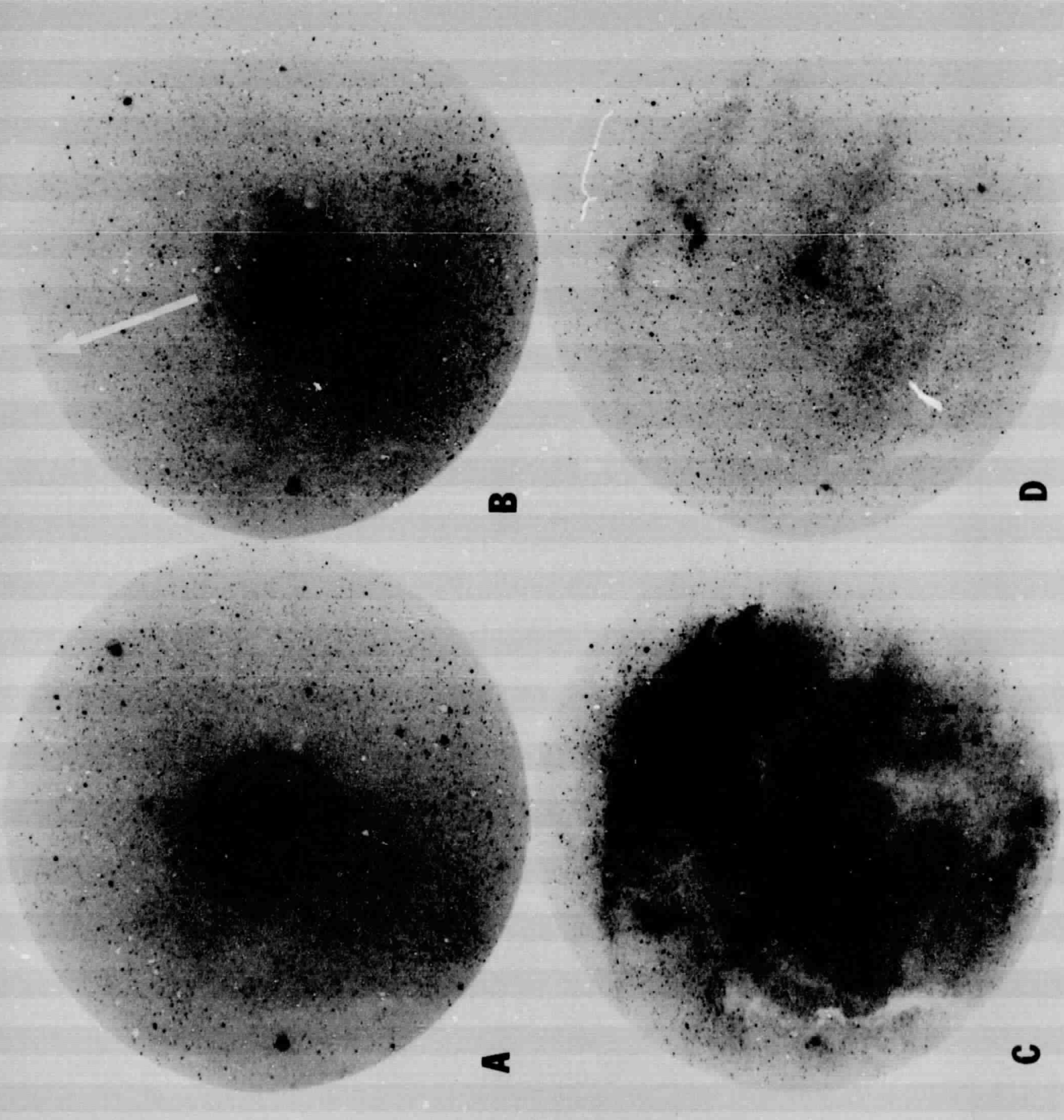
FIGURE CAPTIONS

Fig. 1 - The Orion Nebula as recorded through a 60Å-wide Hβ interference filter using the KPNO 4-meter prime focus camera. The arrow indicates LL Orionis and the arcuate structure around it. Note that the axis of symmetry points toward the bar structure, not $\theta 1$ Orionis.

Fig. 2 - A blown up view from Figure 1 shows the arcuate structure in more detail. Displaced ahead of and behind the structure is the calculated shape (see text).

Fig. 3 - Four passbands of the ζ Ophiuchus H II region are shown here. Figure 3a is through a blue continuum passband (4225Å, $\Delta\lambda$ = 60Å), Figure 3b is through an [O III] passband (5010Å, $\Delta\lambda$ = 28Å), Figure 3c is - through an Hα + [N II] passband (6570Å, $\Delta\lambda$ = 75Å), and Figure 3d is through a [S II] passband (6736Å, $\Delta\lambda$ = 50Å). The arcuate structure is most visible in [O III], and faintly visible in Hα + [N II]. It is not detected in [S II] or blue continuum. The large ring around the star image is a reflection due to the transfer lens located after the image intensifier and the ghost that appears to the side of the star image (indicated in Figure 3a) is due to opposite field reflection off the interference filter. As these plates were recorded, identical frames were recorded of α, δ, σ, π, and τ Sco with the star images in precisely the same position on the camera field. None of the plates show arcuate structures like that seen about ζ Ophiuchus in [O III]. Furthermore, a number of frames recorded with a 135mm camera also detect the [O III] around ζ Ophiuchus. The arrow indicates the proper motion direction of ζ Ophiuchus as published in the FK4 Catalogue.

Fig. 4 - Expanded view of the [O III] arcuate structure around ζ Ophiuchus. Displaced ahead and behind the arc is the calculated shape of the shock.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