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KINEMATICS OF THE HUYGHENIAN REGION OF THE ORION NEBULA

D. FISCHEL
W. A. FEIBELMAN

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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D. Fischel and W. A. Feibelman
Goddard Space Flight Center
Greenbelt, Maryland 20771

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ABSTRACT

The nebular [O II] λ3726 and [O III] λ5007 radial velocity measures of Wilson, et al. (1959) are presented in contour map form. The space motions of θ^1 and θ^2 Orionis, and the nebular measures are discussed. II

Introduction

The Orion Nebula, NGC 1976, has received a large amount of attention in regard to its kinematics. Several extensive studies have been carried out in the past to determine radial velocities of the brighter portions of the nebula. Among these investigations were those of Buisson, Fabry and Bourget (1914), Campbell and Moore (1918) and Baade, Goos, Koch and Minkowski (1933). The most recent and by far the most extensive and accurate spectroscopic study was by Wilson, Münch, Flather and Coffeen (1959) who obtained multislit spectra at the Coude focus of the Palomar 200-inch telescope. For the bright central portion of the nebula they used a dispersion of 4.5 Å/mm and selected four emission lines, λ5007 of [O III], λ3726 of [O II], λ4861 (H-beta) and λ4340 (H-gamma). In Table 2 of the Palomar radial velocity catalog thousands of measured velocities are listed for [O III], [O II] and H for positions in terms of X and Y coordinates in millimeters from the origin. This origin was taken as the location of the brightest star, θ^1C, of the Trapezium, which is believed to be the principal source of excitation of the nebula. The radial velocities of [O III] and [O II] were measured to an accuracy of 0.1 km/sec while those of Hβ and Hγ are accurate to only 1.0 km/sec due to the width of the hydrogen lines. The heliocentric radial velocities for the [O III] and [O II] lines cover a range of from about 6 km/sec to 30 km/sec for the central portion of the nebula. For a limited number of selected outer, fainter regions a dispersion of 9.2 Å/mm was used, but these areas were not considered in the present work. Approximately 100 hours observing time with the 200-inch was used by Wilson *et al*. to secure the 4.5 Å/mm material during the period 1954 to 1956.

In the "General Discussion" section of their 1959 paper the authors stated that their primary objective was to make the vast body of observational material available, without attempting to interpret the data at that time. Apparently there have been no subsequent attempts to plot or otherwise arrange the data in some form that lends itself to analysis, except for the work by Wurm and Perinotto (1965) who plotted a single row of radial velocities through the center of the nebula to show that the [O II] velocities differ from the [O III] velocities for any given point, and that the former seem to be systematically higher than the latter.

Discussion

We have used the Palomar data for [O II] and [O III] of Table 2 of Wilson, *et al*. between the limits of $\overline{X} = \pm 80$ mm and $\overline{Y} = \pm 60$ mm to construct the pair of contour maps in Figure 1 of iso-velocities in 2.5 km/sec intervals. Each map represents about 15,000 data points and is essentially complete within the above limits. In a few places the data were not accurate to 0.1 km/sec (indicated by an asterisk in Table 2 of Wilson, et al.). These positions clearly showed line splitting, probably due to separate nebular condensations, and the tabular values are the mean values to the nearest 1 km/sec.

A proprietary computer program, the General Purpose Contour Plotter (GPCP, California Computer Products), was used to draw the contours. The program essentially performs a non-linear weighted least squares interpolation over the nine nearest data points encompassing the region in which it is searching for contours. On the first try at plotting the $\lambda 5007$ contours some abrupt discontinuities appeared. This was traced to a small printing error in the original publication where some of the Y-coordinates appeared double valued. (A vertical line separating the left hand from the right hand Y-values was not printed.) About 10 percent of the data were affected, but after the corrections were made (Münch, 1971) the discontinuities disappeared.

In Figure 2, the area of the contour maps is marked upon a photograph of the central portion of the Orion Nebula taken by one of us (W.A.F.) in 1963 at the Allegheny Observatory.

Although we will not definitively interpret these contour maps in terms of the voluminous observational data and theoretical models of Orion, certain aspects are evident in the velocity contours:

1) The highest radial velocities of [O III] and [O II] are found

a) in a small area surrounding the O-type star $\theta^1 C$, and

b) in the optically brightest portion of the nebula, 45 arc sec north west of $\theta^1 C$.

In general, bright areas are strongly correlated with high radial velocities.

2) The radial velocities fall off in all directions from $\theta^1 C$.

3) When the other stars of the Trapezium are superimposed on the contour maps it appears that A, B and D have considerably less effect on the kinematics than C does.

4) A "trough" of low velocity runs diagonally across the nebula, from top center to middle right, corresponding to the dark portion parallel to the bright ridge near θ^2 Orionis.

5) As evident from the data listing itself and demonstrated by Wurm and Perinotto (1965), the [O II] velocities are in general greater than those of [O III], and the areas of high radial velocity are larger in [O II].

The stellar radial velocities (Wilson, 1953) and proper motions (Strand, 1958) give galactic longitudinal tangential velocities of -11 to -30 km/sec for the six stars in θ^1 and θ^2 relative to their local standard of rest, i.e., toward lower galactic longitude.

Although some of this motion must be internal to the multiple star systems involved, there is clearly a negative tangential velocity. The reflex solar motion and differential galactic rotation radial velocities are 18.4 and 5.9, respectively, (=24.3 km/sec) which leaves only small residual radial velocities for the stars. Table 1 lists the star, observed radial velocities in km/sec, observed and calculated proper motions in 10^{-3} arc sec/yr., peculiar radial, longitudinal tangential, latitudinal tangential and space velocities in km/sec.

However, the nebular radial velocities, after removal of the reflex solar and differential galatic rotation effects, puts the 25 km/sec regions essentially at rest and the "trough" between θ^1 and θ^2 moving at 12.5 km/sec toward the sun. These considerations imply a kinematic model of the nebula wherein, the stars in θ^1 were formed behind the Dark Bay ($\sim$30 arc sec away), emerging some 10^4 years ago. The radiation from these stars accelerated the Dark Bay material and we see it still moving toward us. Similarly, radiation from both θ^1 and θ^2 are pushing material toward each other, resulting in the trough being squirted out towards the sun. The bright areas (at 25 km/sec) N and W of θ^1 are currently being excited and accelerated by the Trapezium stars.

It has been argued that the velocity differences between [O II] and [O III] are not due to optical depth effects because the velocities in [O III], [Ne III] and HeI λ4471 all agree (Münch, 1964). Such an argument may not be valid, since these transitions arise from upper states whose lifetimes are 50 seconds (λ5007 being the longest), whereas the upper state of [O II] λ3726 has a lifetime of $\sim 6 \times 10^3$ seconds. Furthermore, HeI λ4471 (1s2p- 1s4d) must be connected to the trapped λ10830 (1s2s-1s2p) radiation (Munch and Persson, 1965). The additional complications of extensive condensations (apparent even in Figure 1) and turbulence only makes the interpretation of what we see in the velocity measures more unclear. If a condensation moving at the local standard of rest were sufficiently far from the exciting stars and rarefied such that it emitted only previously excited [O II], then one cannot explain why the condensation in the line of sight emitting [O III] and moving away from the nebula does not emit [O II]. Invocation of an optical depth effect, which would have to be continuum because of the velocity shift, only raises the problem of why [Ne II] λ3868 differs in radial velocity from [O II]. A possibility, not investigated here, is that a laser effect occurs, due to continuum nebular radiation passing through remote condensations and/or homogeneous matter in the arm. If such a phenomenon were possible, Orion is the most likely nebula in which to find it, since Orion has a higher surface brightness (Pottasch, 1963) than other objects, a strong continuum radiation field and exceptionally strong [O II] λ3726 radiation.

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Table 1

Motions for 6 stars in the Orion Nebula

Star	V_r	μ_x $\times 10^3$	μ_y $\times 10^3$	$\mu_l \cos b$ $\times 10^3$	μ_b $\times 10^3$	V_{rp}	t_{lp}	t_{bp}	V_{sp}
θ^1 A	33.4	1".4	-2".8	-3".183	0".153	9.1	-25.57	0.377	27.14
B	24	-3.7	-8.0	-5.283	7.255	-0.3	-30.75	17.88	35.57
C	28	-8.3	-5.7	-0.960	10.184	3.7	-20.10	25.10	32.39
D	31	3.1	1.7	-0.023	-3.590	6.7	-17.79	-8.85	20.97
θ^2 A	35.6	-1.2	2.2	2.551	-0.032	11.3	-11.44	-0.08	16.08
B	28.5	-1.3	-1.5	-0.690	1.897	4.2	-19.43	4.68	20.42

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Fig. 1 - Radial Velocity Contour Map of the Central Portion of the Orion Nebula

a) λ 3726 [O II]

b) λ 5007 [O III]

The scale and legend are the same for a) and b).

Maximum dimension for each map is approximately 3.5 arc-min. The 4 stars of the Trapezium, θ'A, B, C and D, are shown as white circles. A very small area of 25.0 km/sec is hidden by the white circle of θ'C for the [O III] map and a similar high velocity section is displaced from θ'C for the [O II] map.

The extreme left-central region of the [O II] map has a small area of 27.5 and 30.0 km/sec velocities.

Fig. 2 - The central portion of the Orion Nebula taken in the wavelength region λ6300 - λ6700. The T-shaped area outlined in white corresponds to the approximate area of Fig. 1a and b. Several features referred to in the text are identified. The arrows GP and NP point towards the galactic pole and north pole, respectively. The Dark Bay, Bright Bar and Trough are identified, as are the stars θ^2A and θ^2B. The brightest star near the center is θ^1C, with the other stars, (A, B and D counterclockwise from C) completing

the Trapezium. The arrow at θ'C indicates the direction of its latitudinal tangential velocity, t_{lp}, of 20 km/sec. Corresponding values, in the direction parallel to θ'C, for the other 5 stars are listed in Table 1.

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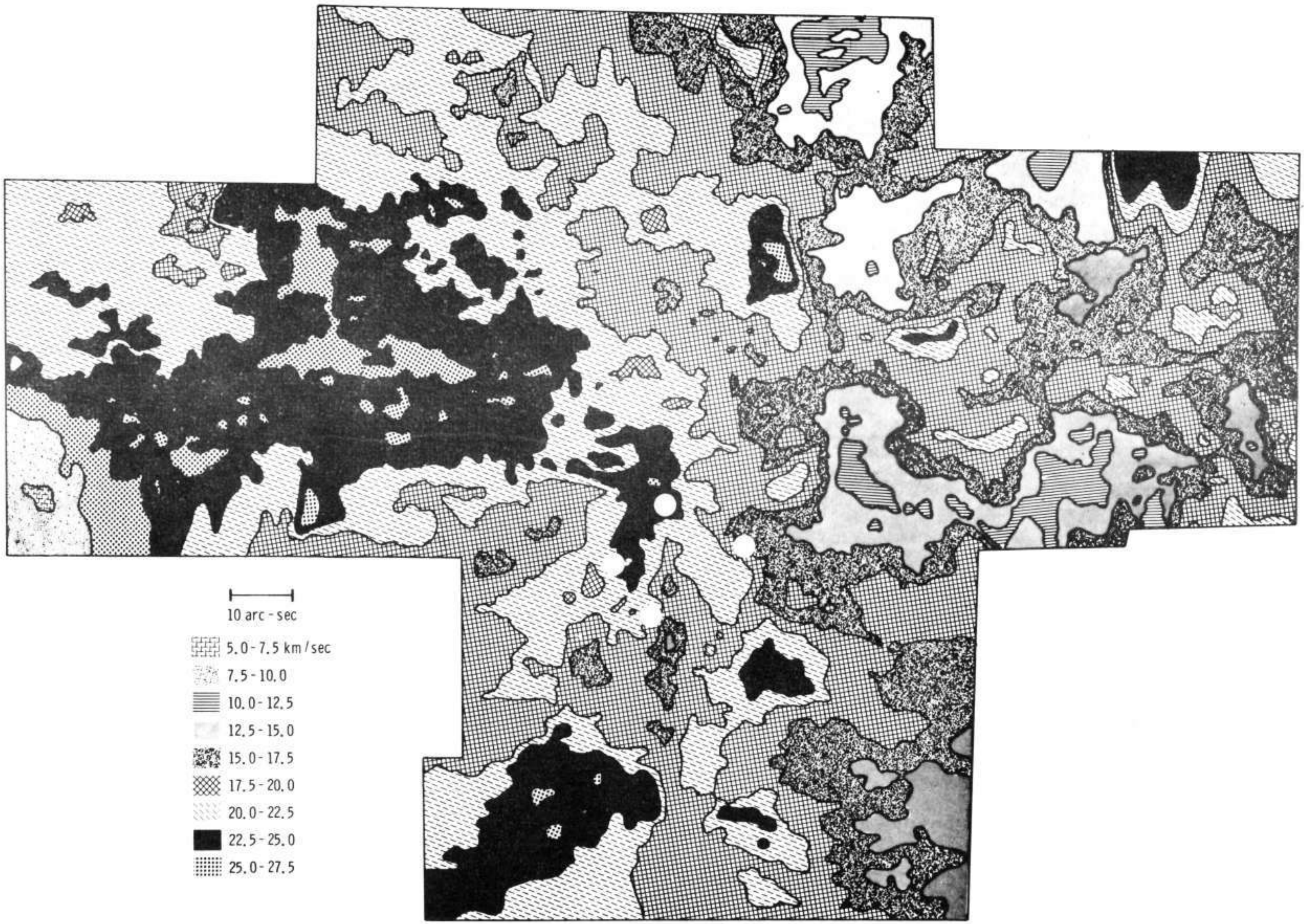
10 arc - sec
5.0 - 7.5 km/sec
7.5 - 10.0
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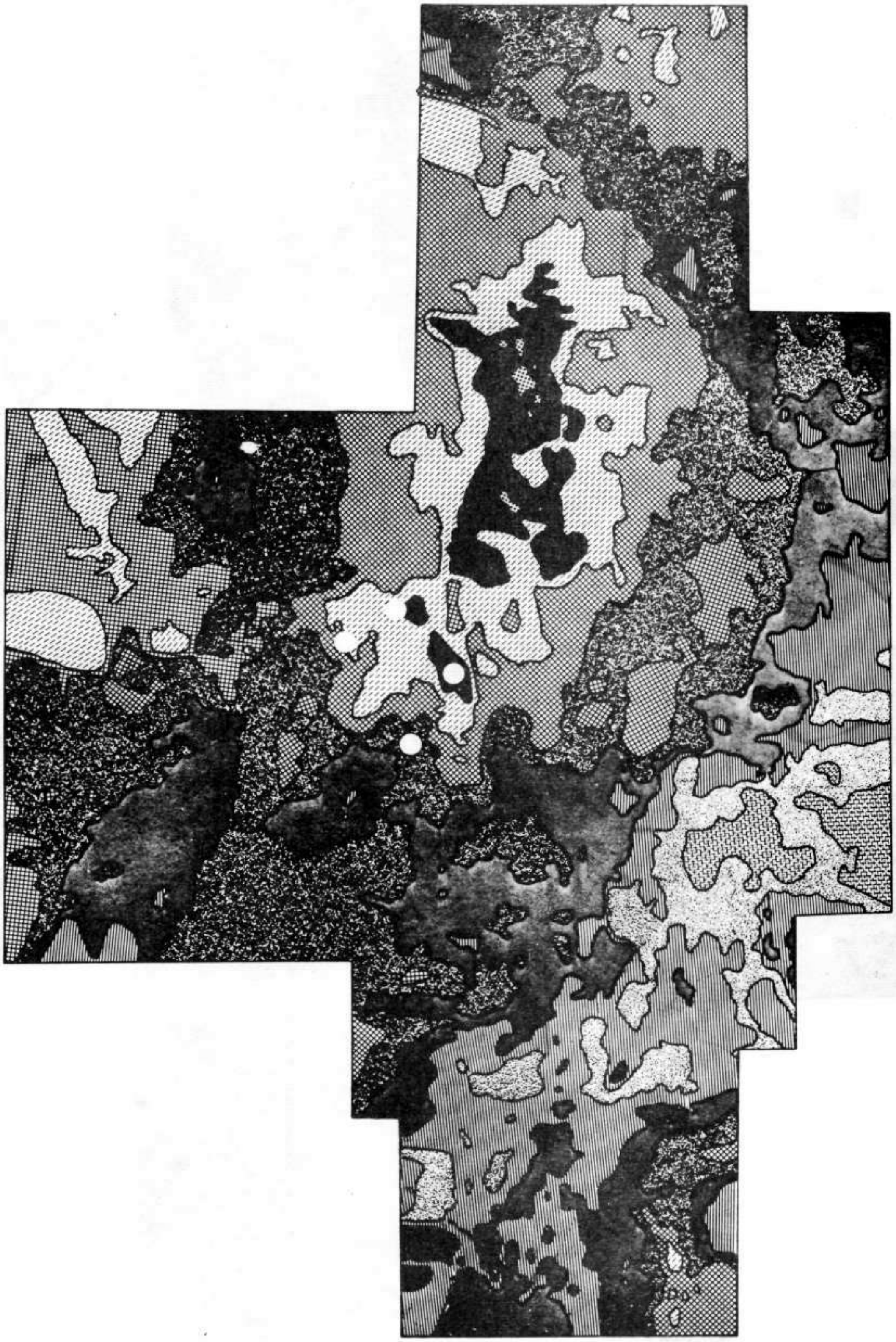

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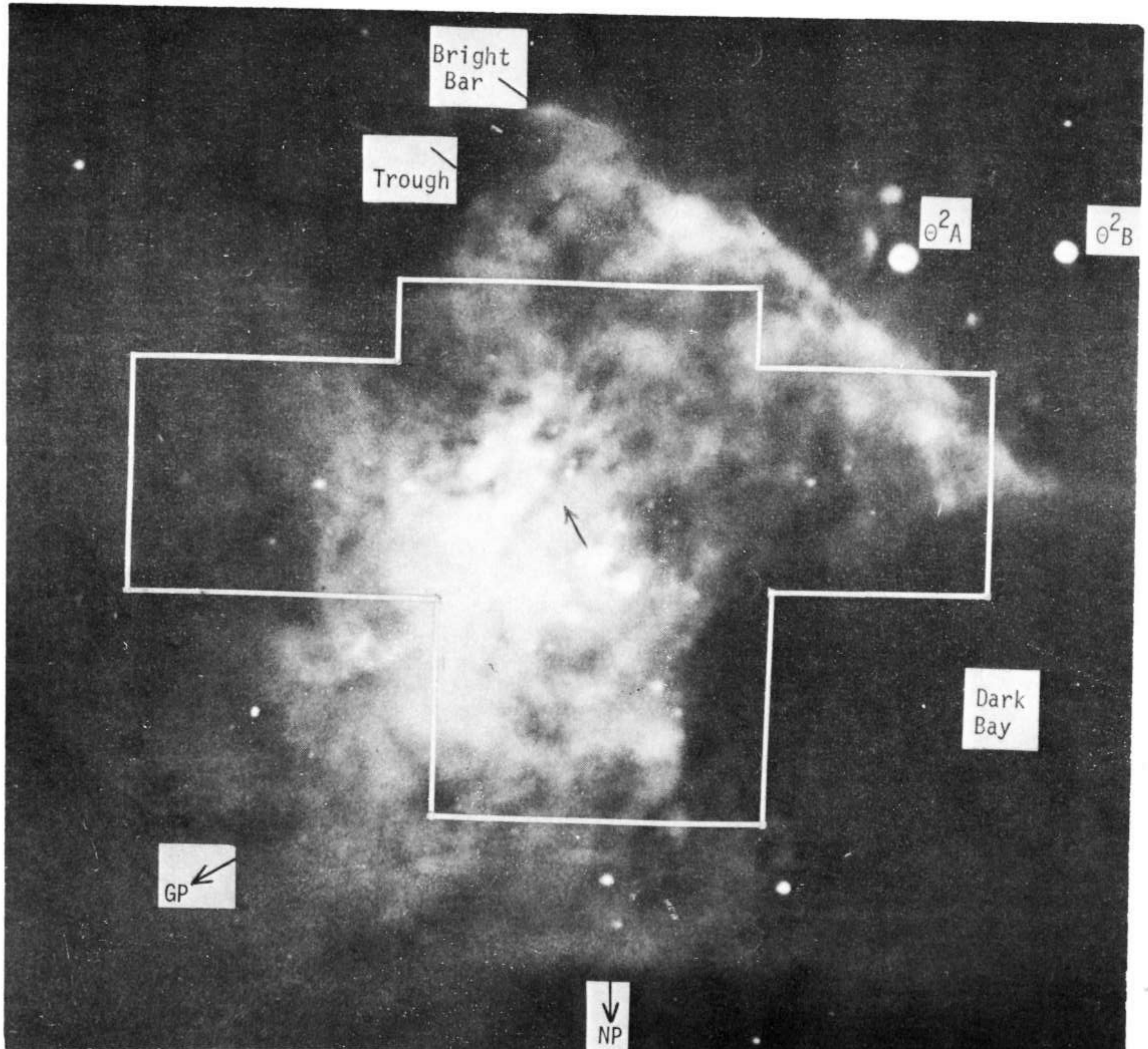

Fig. 2