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THE STRUCTURE OF THE ORION NEBULA

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The Orion nebula is the best studied of all H II regions. The experimental data of this nebula are reviewed, and interpretive models of the structure of both the nebula and its environs are developed. The H II region is composed of an inner 3′ core surrounding the exciting star θ^1C which is partially imbedded on the near side of a massive neutral complex. A network of strong flows results that resupplies high-density ionized gas to the core region. Gas in the core then freely expands where possible, primarily into the foreground, south, and west. Details of this model are compared with optical, radio, and infrared observations of the ionized, neutral atomic, and molecular gas in the Orion nebula. The nature of the neutral complex is also discussed.

Key words: H II regions — neutral gas complex — Orion nebula

I. Introduction

The Orion nebula is the brightest and best studied of all H II regions, and has served as a focal point for many interesting experiments over the past few decades. A vast body of experimental data has now been collected, and yet no clear picture of the nature of the nebula has emerged. Many attempts have been made to develop models for the nebula, but none have withstood the many experimental tests that followed their presentation. Nonetheless, much progress has been made over the past several years in understanding the structure of the nebula, and it is safe to predict that much more progress will be made in the near future.

In this paper we attempt to present a timely review of the best available data and to develop an integrated model of the H II region and its environs. The first part of the paper is devoted to the ionized nebula. We begin with a review of the most basic data. Then we develop a model of the structure and give some theoretical justification for parts of it. The model is best described as a semiempirical and somewhat ad hoc synthesis of older concepts and new ideas prompted by recent experiments; many of the concepts date back to models proposed by Wurm (1961). Zuckerman (1973) arrived independently at a very similar model based on a somewhat different point of view. We then return to the data to show that the model serves as an adequate framework for its interpretation.

In the last part of the paper we shall discuss the massive neutral complex out of which the nebula presumably formed. A simple interpretive model is also developed for this region. This complex has been the subject of active investigation by infrared and molecular-line observers over the past five years (see also the recent review by Wynn-Williams and Becklin (1974) in these *Publications*).

Finally, we briefly explore the possibility that important aspects of this model are applicable to other H II regions.

In this paper we shall abbreviate north, east, south, and west with the symbols N, E, S, and W, respectively.

II. Basic Data

The H II region Orion A is located in a large

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complex of neutral clouds, stellar associations, reflection nebulae, and other H II regions extending over a 10° × 10° region shown in Plate I (other well-known features in the region include the Horsehead nebula, Orion B (NGC 2024), and Barnard's Loop). The optically visible portions of Orion A consist of the bright nebula M 42 in the southern part of this region along with the smaller M 43 which lies 10′ to the NE of M 42. At both optical and radio frequencies Orion A is one of the brightest, and thus best-studied, of all ionized nebulae. The nebula has been intensively investigated for many years, although the large amount of data available often seem to complicate our understanding of Orion more than it has helped it.

A map of the continuum radio isophotes observed at λ1.95 cm is shown superimposed on an optical photograph of Orion A in Plate II (taken from Schraml and Mezger 1969). Because they are not affected by obscuration, the radio isophotes provide a good indication of an average density distribution (on the plane of the sky) at frequencies where the optical depth is small, i.e., wavelengths less than about 20 cm. With resolutions of 2′ (as in Plate II), the radio observations show a relatively simple picture. The density distribution consists of a Gaussian with a width of 3′ or 4′ (0.5 pc) and central

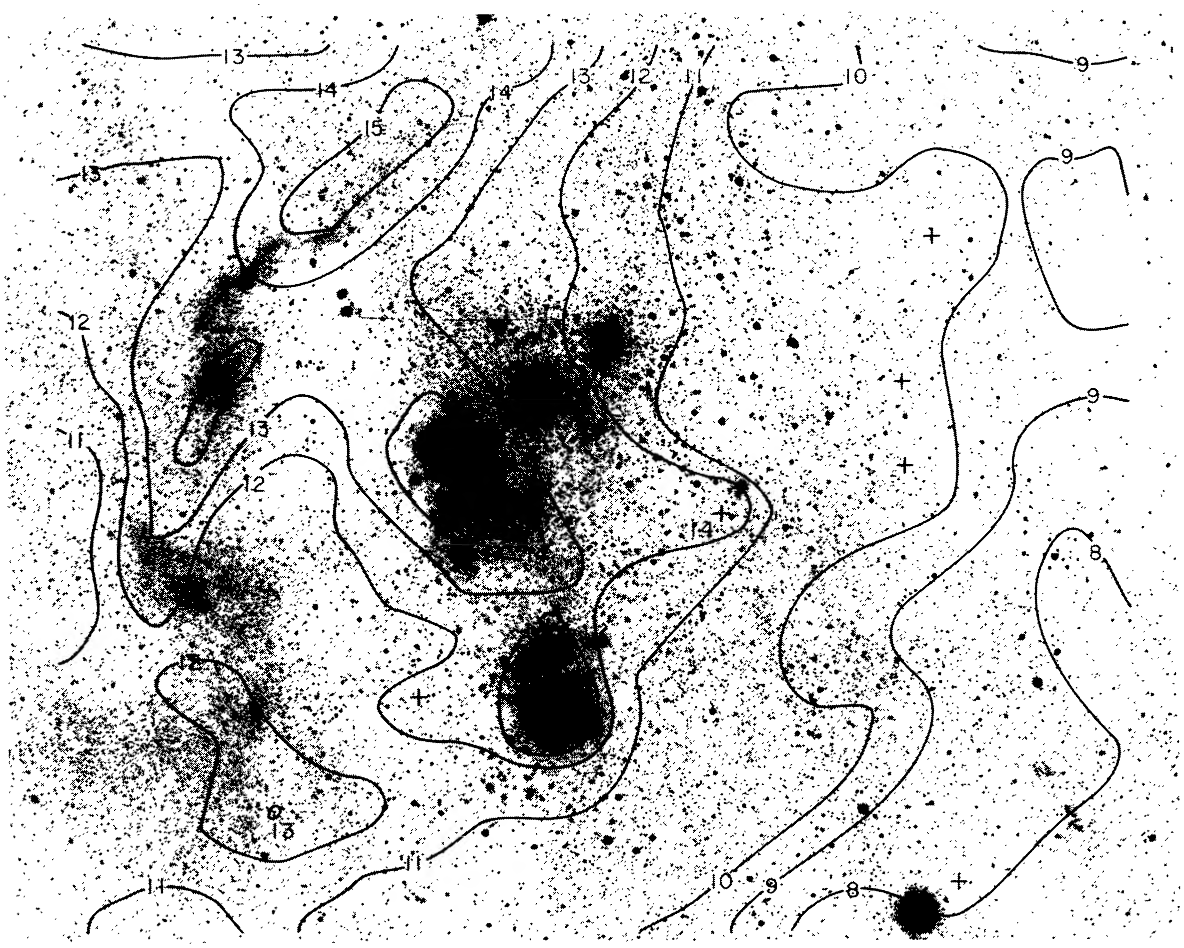

PLATE I

A photograph of the Orion region in the light of Hα covering an area of about $(10°)^2$. Superimposed on the photograph are low-resolution radio continuum isophotes as measured by Rishbeth (1958) at a wavelength of 3.5 m. Orion A (M 42) is coincident with the brightest radio emission. Other features include NGC 1973-5-7 adjacent to Orion A in the north, the Horsehead nebula (about 3° NE of Orion A near the secondary radio peak at contour level 15), Orion B (about 0.°8 NE of Orion A), and Barnard's Loop (about 3° E of Orion B along the ridge of radio emission).

density of $\sim 10^{3.5}$ cm^{-3} centered very close to the Trapezium and optical center. This Gaussian is superimposed on a much weaker and extended "plateau" which falls off rapidly at a distance of $\sim 10'$ except to the SW. From these measurements and those at other frequencies it is clear that the interior Gaussian "core" becomes optically thick at radio frequencies less than 1 GHz or 2 GHz.

Radio synthesis observations (Plate III) show that higher-density fine structure is superimposed on the core (Webster and Altenhoff 1970). These "condensations" have densities of $10^{4.5}$ cm^{-3} (or higher if optical depth effects are important at their observing wavelength of λ11 cm), and are distributed within 30″ of the center of the core. The two brightest radio features coincide with the brightest optical emission west of the Trapezium and the tip of the dark bay to the east.

Optically, structure can be found with all size scales (Wurm and Perniotto 1962; Münch and Wilson 1962). Plate IV contains a high-quality photograph of Orion taken with the 4-m Mayall telescope at Kitt Peak National Observatory in the light of [S II] λλ6717–6731 (courtesy of T. R. Gull). The core region is the dark area near the center of the photograph. The brightest optical nebulosity is found in the western parts of the core. The prominent dark bay, optical filament or "bar", dark lane, and M43 are indicated schematically in this plate (many of these same features can also be seen in Plates II and III). On larger-scale sizes the

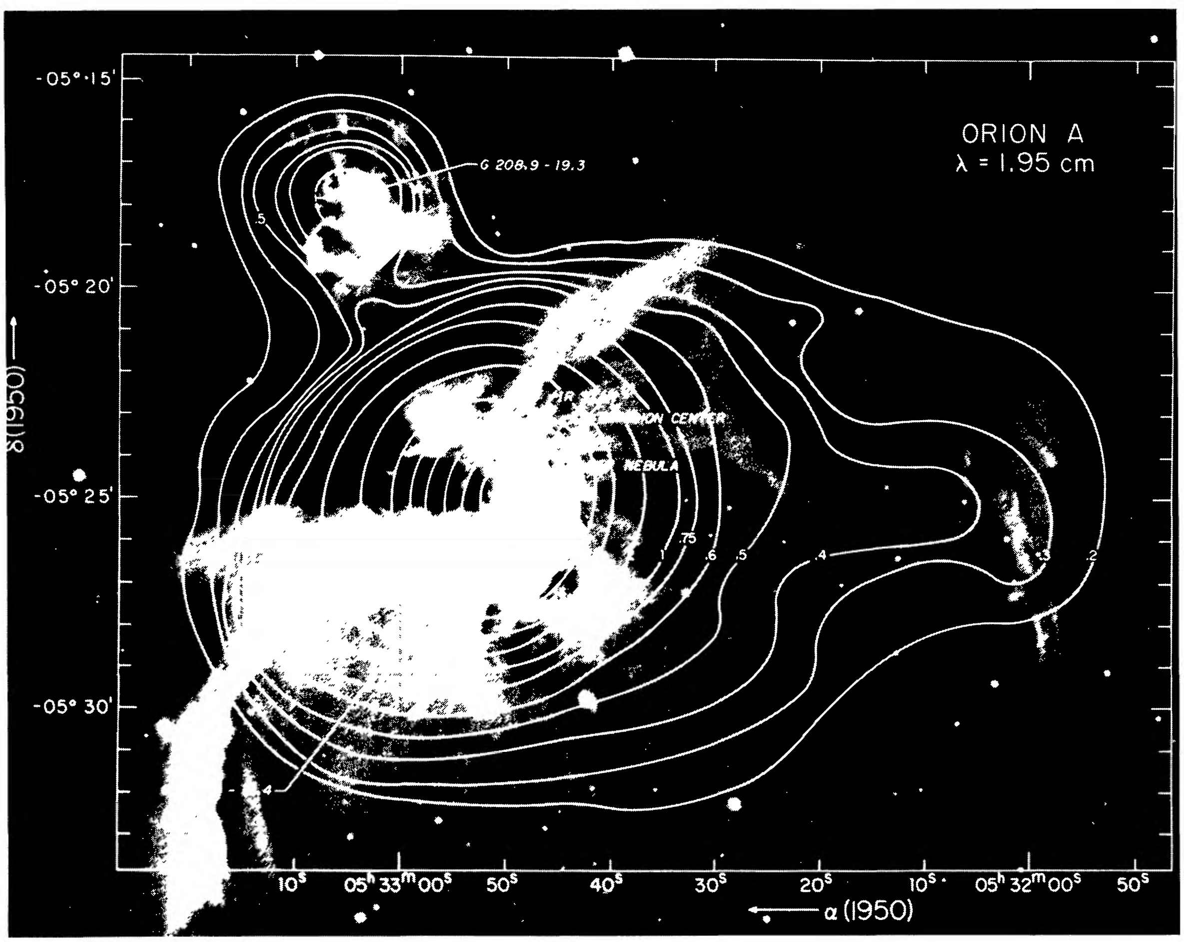

PLATE II

The radio continuum isophotes of Orion A at λ1.95 cm, taken from Schraml and Mezger (1969) and used with permission. The spatial resolution is 2′. (Schraml, J., and Mezger, P. G. 1969, *Ap. J.* **156**, 269. Copyright 1969, The University of Chicago Press.)

optical nebula looks similar to the single-dish radio map (Plate II) except for the dark bay and lane.

Located at the center of the core are the four so-called "Trapezium" stars. The southernmost of these, θ^1C, is an O6 star thought to provide all of the ultraviolet excitation for M 42.

Analysis of line observations have corroborated this relatively simple picture of the density distribution. At radio frequencies, recombination lines have been studied by Hjellming and Gordon (1971) and by Brocklehurst and Seaton (1972). The first group reports electron densities, $N_e \sim 10^{4.3}$ cm^{-3} and electron temperatures, $T_e \sim 10^{4}$ ° K in those regions which contribute most to the line radiation. These results agree well with the radio synthesis observations, the optical studies (see below), and

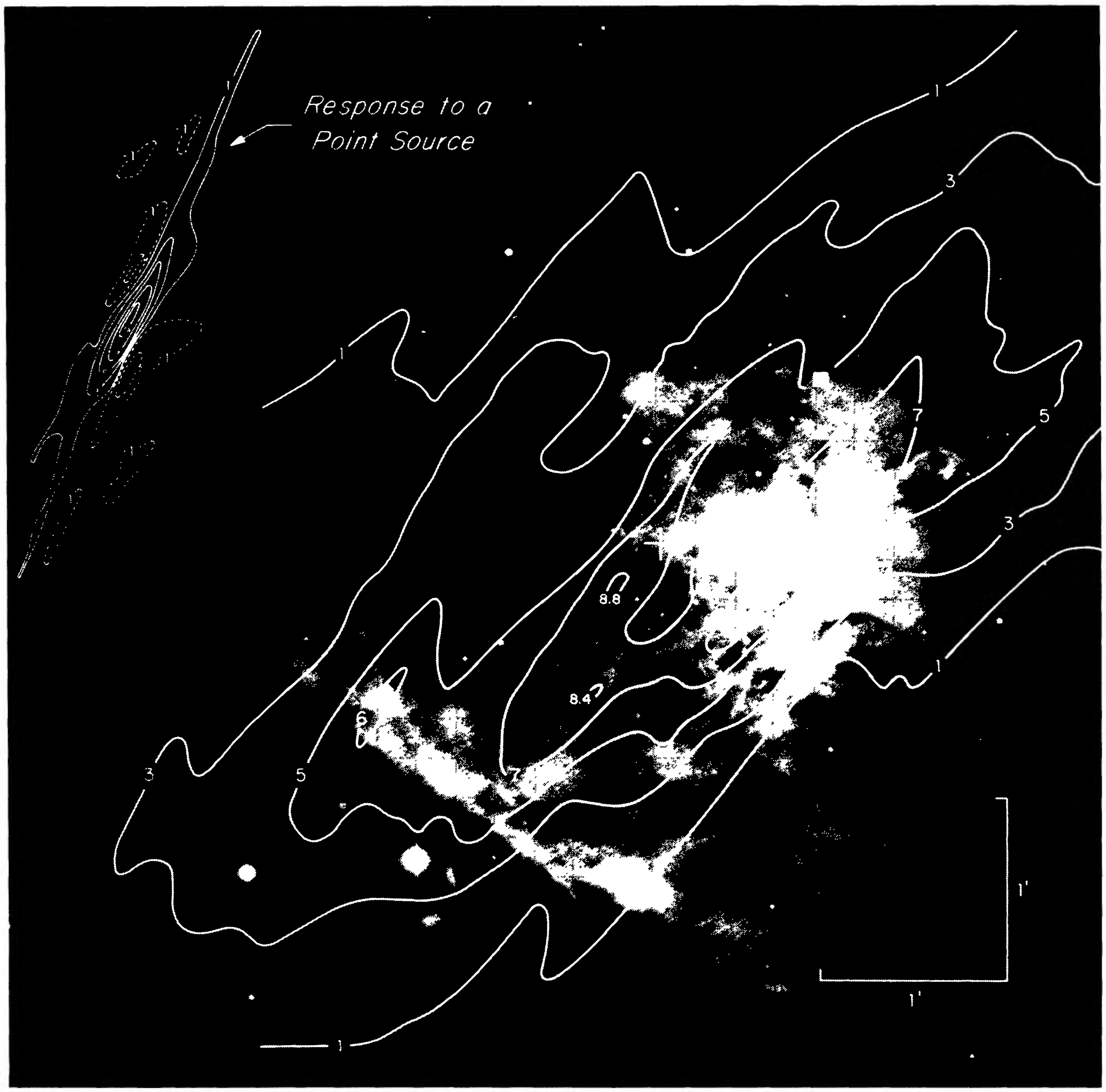

PLATE III

The radio continuum synthesis map of Orion A at λ11.1 cm, taken from Webster and Altenhoff (1970) and modified for display with permission. The half-power dimensions of the synthesized beam are ~ 7″ × 30″. The cross, triangle, and square indicate the position of the radio continuum peak, Kleinman-Low infrared nebula, and the Becklin-Neugebauer infrared point source, respectively.

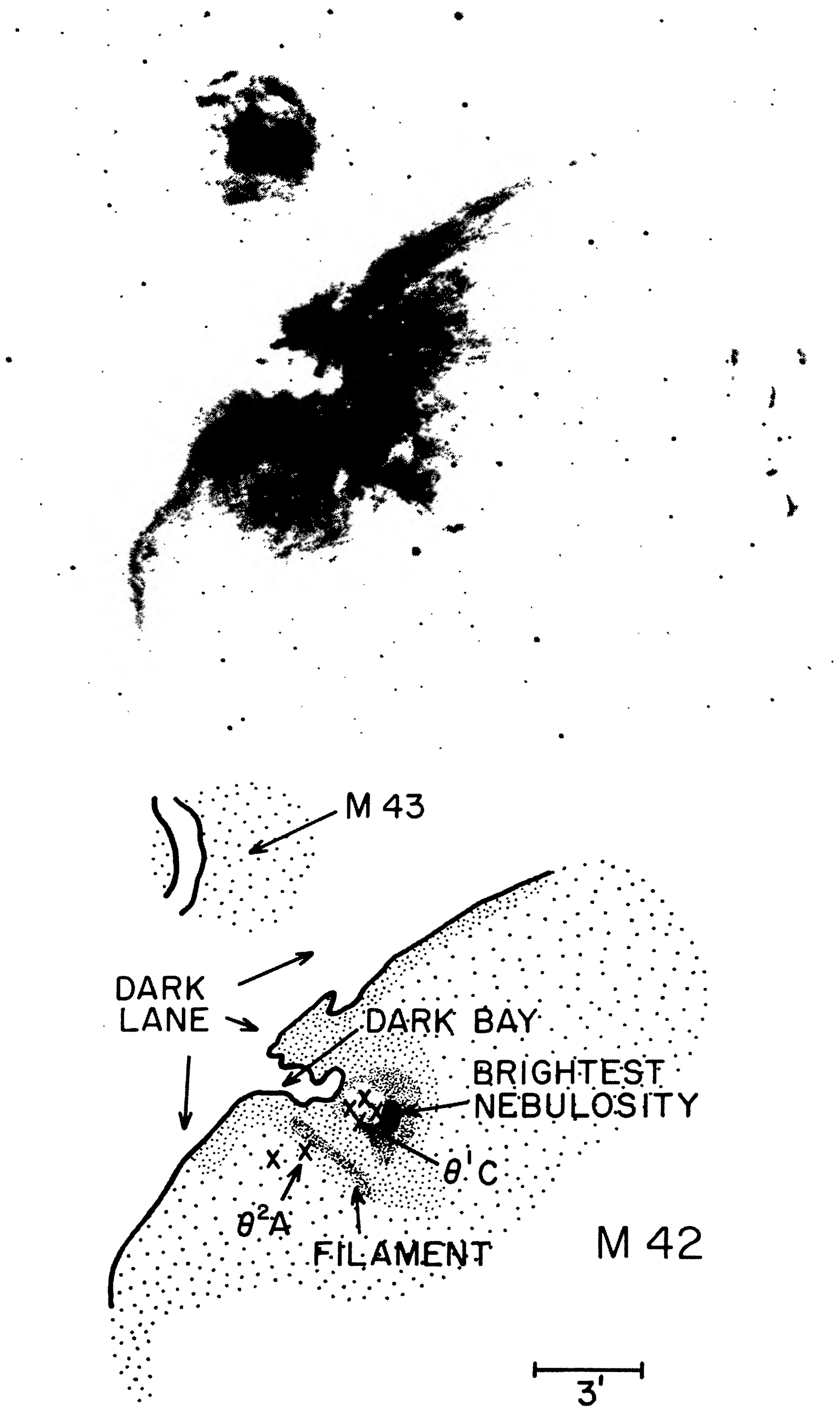

PLATE IV

A high-quality photograph of Orion A taken with the Mayall 4-m telescope in the light of [S II] λλ6717–6731 (courtesy T. R. Gull and the Kitt Peak National Observatory). The positions of important optical features are indicated schematically.

the values determined by this method in many other H II regions (Andrews, Hjellming, and Churchwell 1971). They also determine a size scale of $\sim 30''$ in good agreement with the optical photographs (Plates II and III). Brocklehurst and Seaton (1972) have made a careful analysis of the radio line and continuum observations. Assuming a density distribution consisting of uniform spherically symmetric shells centered on the core (we later question their geometric assumption), they find a good fit to the data results for a peak $N_e \sim 10^{4.2}$ cm^{-3}. The density falls to a value of $10^{3.7}$ cm^{-3} at a distance of 0.15 pc ($1'$) and to 10^3 cm^{-3} at 0.4 pc ($3'$). T_e is 9500° K throughout. Admittedly, their model is nonunique.

Optical determinations of N_e and T_e yield similar results. Forbidden lines of O^+ and S^+ show peak densities reaching 10^5 cm^{-3} over small distances in the brightest regions (Danks and Meaburn 1971; Osterbrock and Flather 1959). Projected onto the sky, the density profile drops by an order of magnitude within 0.3 pc ($2'$) of the peak (Elliott and Meaburn 1973; Danks and Meaburn 1971), and falls off approximately exponentially. These results can be reconciled with the radio observations if there is clumping along the line of sight. Temperatures have been determined optically by many groups (e.g., Goad, Goldberg, and Greenstein 1972; Dopita 1972; Dyson and Meaburn 1971; Peimbert 1967); typical values range from 7500° to 10,000° K. It appears the temperature rises by $\sim 20\%$ (or more) from the center of the core to the edge (Bohuski, Dufour, and Osterbrock 1974).

In sharp contrast to the somewhat symmetric picture indicated for the density distribution is the picture indicated by the velocity distribution. Kinematically, the core region is very active showing a wide range of velocities both as a function of position and line excitation. At radio frequencies, observations with $3'$ resolution show the velocities to change from 8 km s^{-1} (relative to the LSR) at about $5'$ NE of the peak near M43, to -2 km s^{-1} at the peak of the core, to ~ -5 km s^{-1} $5'$ toward the SW (Balick, Gammon, and Doherty 1974, hereafter referred to as Paper I). Further to the west, the velocities become increasingly positive (Mezger and Ellis 1968). Interestingly, the line profile at high resolution ($3'$) is well-fit at all points by a single Gaussian component whose width varies only slightly (Paper I). Results of helium line analysis are in substantial agreement with the hydrogen results. However, recombination lines of C^+, which arise from neutral gas on the periphery of the nebula, show a broader spatial distribution than the ionized hydrogen and an average velocity of 9.7 km s^{-1} with little, if any, variation. The carbon linewidth (at half intensity) is narrow ($\Delta V \sim 4$ km s^{-1}), and it is likely that the boundary of the nebula is quite cold ($T \leqq 50°$ K) and dynamically quiescent compared to the H II region (Paper I). Much the same is true for regions where the molecular and neutral hydrogen lines associated with Orion A are formed (see below).

Optically, there have been many excellent kinematic studies of Orion A. Observations with high spatial resolution have been made of hydrogen (Fisher and Williamson 1970) and forbidden lines of oxygen (Elliott and Meaburn 1973; Wilson et al. 1959) and nitrogen (Deharveng 1973). These show that velocities can change rapidly between regions separated by only serveral seconds. In addition, line splittings of up to 25 km s^{-1} have been observed in several places for the forbidden lines (Meaburn 1971; Dopita, Gibbons, and Taylor 1973, and references cited therein). Weak lines at velocities ~ 50 km s^{-1} may have also been detected over localized regions.

The macroscopic distribution of velocities determined optically is complex. At many points in the core it is possible to find a wide range of velocities represented. Consider, for example, the Hα studies of Fisher and Williamson and [O III] results of Wilson, et al. which show that, in general, the bright optical feature is blue-shifted relative to most of the gas nearby. However, the kinematic picture obtained elsewhere in the core region is a function of the optical line studied (implying that in most directions, conditions of excitation vary along the line of sight). For the Hα line, which is emitted everywhere in the ionized gas, there is a tendency to reddened velocities, relative to the bright area, toward the dark bay (in corroboration of the radio results); however, weaker blue-shifted gas can be found in this direction as well.

Kaler (1967) has reported results obtained earlier by Wilson which show that there is a strong dependence of species velocity on the photon energy required to create the various species. For example, ions such as Fe^+ and Fe^{++}, which are ionized at low photon energies, show velocities of ~ 9 km s^{-1}, much like the C^+ seen at radio frequencies. There is a sharp change in velocities of ions requiring conditions of higher excitation (Fig. 1). Thus species such as S^{+++}, O^{++}, and Ne^{++} have velocities much like the radio hydrogen lines of -2 km s^{-1}, whereas N^+ and O^+ are found at intermediate velocities. Obviously, there exists significant velocity stratification along at least this one line of sight through the bright optical portion of Orion A. The Hα and [N II] results of Dopita (1972), Dopita et al. (1973), and Deharveng (1973) show that much the same sort of behavior exists elsewhere.

Many other observational results are available both at optical and radio frequencies. We shall defer our discussion of these results so that we can introduce the basic model. We return later to these other observations to refine the model further and to show that no major inconsistencies exist between the model and the observational results.

III. The Model

The basic geometry of the nebula and surrounding material was presented in Paper I and is shown in Figure 2. To first order, the model consists of a "core" H II region surrounding θ^1C which is an ionized "cavity" partially

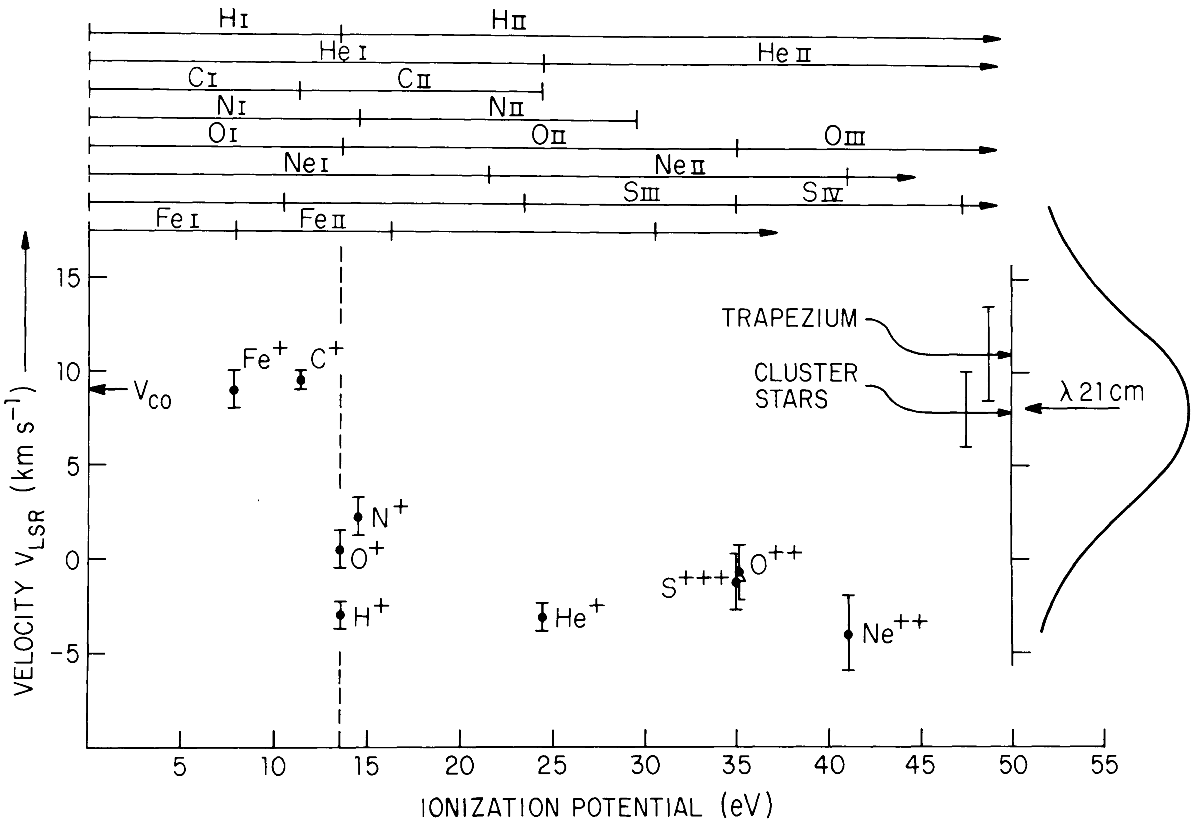

FIG. 1 — The observed velocities of optical lines in the brightest optical nebulosity are plotted as a function of the minimum photon energy required to produce the ionized species (adapted from Kaler 1967). The velocity of carbon monoxide is indicated on the velocity axis. Optical hydrogen and helium lines have not been included because their line shapes are known to be complex. The H, He, and C velocities are from radio recombination lines. On the right are shown the mean velocity of the stars in the Orion cluster and the velocity of the Trapezium stars alone (Johnson 1965). Also sketched is the average λ21-cm emission profile of atomic hydrogen within 30′ of the Orion nebula (Radhakrishnan et al. 1972).

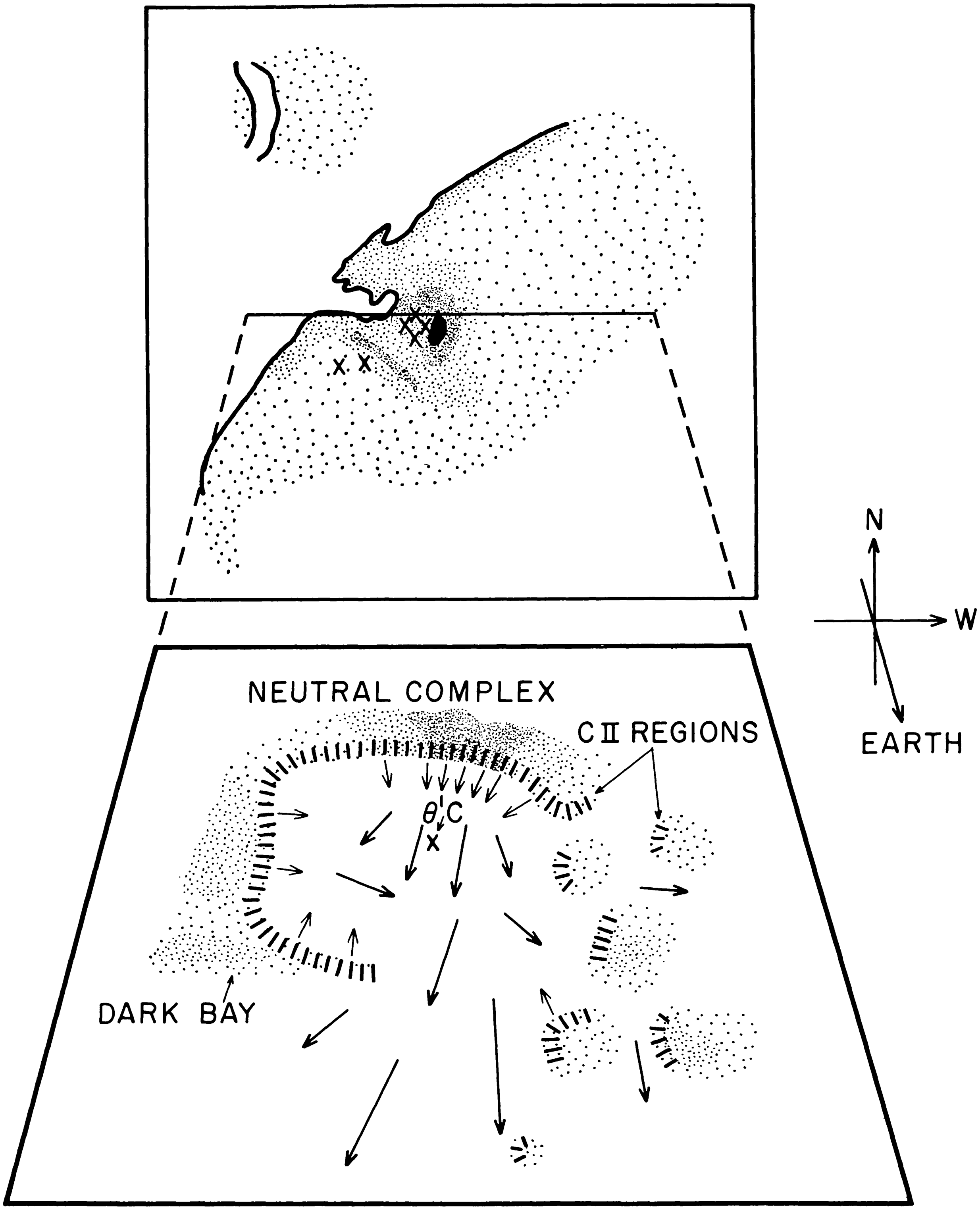

FIG. 2 — A schematic diagram of Orion A showing the flow pattern. The lower portion of the figure represents a cross section through the nebular center in the E-W direction along the line of sight. The star in the lower portion is θ^1C, the cross-hatched area is the region of C II emission, and the dot pattern indicates probable density fluctuations in the neutral gas.

imbedded on the near edge of a large neutral complex that contains the molecular clouds and infrared sources. Ultraviolet radiation from θ^1C has apparently ionized the core and much of the material in the foreground and toward the south and west, although higher-density fragments of the neutral cloud may yet exist near the core in these directions (e.g., the dark bay). Behind the nebula, and to the east and north is the high-density neutral complex out of which the nebula formed.

Relatively undiluted ultraviolet radiation from θ^1C falls on the dense neutral gas to the E, N, and rear of the core creating newly ionized gas whose densities lie between about 10^3 and $10^{4.5}$ cm^{-3} (as observed). In other directions there exist regions of much lower density, so that two important processes governing gas motions come into play. First, because there are no large temperature gradients in H II regions, density gradients in the core imply pressure gradients which drive gas from the core into the more vacuous surroundings (free expansion) to the S, W, and front. Second, gas is resupplied to the core region by photons which ionize neutral gas to the E, N, and rear. The precise geometry for the inflowing gas is critically dependent on the distribution of neutral gas around the core. Nonetheless, a system of "flows" of ionized gas, mostly from the E, N, and rear, mix with the ambient gas in the core region and eventually disperse from the core into the outer environs to the S, W, and front. The nature of these flows will be discussed shortly.

Such a model naturally accounts for the large-scale density distribution determined by single-dish radio measurements. The high-density gas in the core is continuously resupplied from newly ionized gas, and in turn this gas resupplies the large radio-continuum plateau as it disperses. Inside the core there are some predominant flows; apparently one of these is coincident with the high-brightness radio and optical source 30″ west of the Trapezium. This is the "primary" flow and is directed essentially toward the observer along the line of sight. The sonic-like velocity of this flow relative to the neutral gas nearby (see below) helps explain the H II-C II velocity difference of $\sim$11 km s^{-1} observed in this direction (Paper I).

In the direction of the primary flow the line of sight intercepts freely expanding low-density foreground gas, high-density ionized gas in the flow (both with about the same velocity), and the ionization front behind the flow. It appears that gas of the primary flow dominates the kinematics in this direction because observations of bright high-excitation optical lines formed in the flow (such as [O III]) agree in velocity (-2 km s^{-1}) with the radio hydrogen lines formed everywhere along the line of sight. Lines of lower and intermediate excitation reported by Kaler (1967) undoubtedly arise in the ionization front on the far side of the flow, hence their velocities are intermediate between H II and C II (Fig. 1). Here we assume that gas in the flow is optically thin to visible light; Smith and Weedman (1970) and Weedman (1966) argue convincingly that this is the case.

Previous models which have been able to explain the density distribution have generally failed to account for some important aspect of the observed kinematics, and vice versa. In the present model, the velocity pattern on size scales of the flow diameter ($\sim 1'$) is explained by the relative placements of flows and the neutral gas. As we have discussed, the primary flow dominates the kinematics in the region of the brightest optical and radio luminosity. Elsewhere there are secondary flows which are indicated schematically in Figure 2. In the E and NE where both the H II and C II velocities are observed to be nearly the same, we hypothesize that either there exist weak flows whose net velocity is directed perpendicularly to the line of sight, or that the geometry of the neutral gas allows no escape for the H II in this vicinity (this is a "backwater" region), or both. As one moves closer to the core, the effect of gas associated with the primary flow increasingly dominates the observations, and the average gas velocity changes from $+9$ to -2 km s^{-1}. Turbulent gas in the core and freely expanding gas in the foreground (primarily blue-shifted with respect to the primary flow) can also be seen in the superposition around the core along the line of sight.

A few arc minutes to the S and W of the primary flow, much of the gas along the line of sight is confined in channels between remnants of the original neutral complex. This accounts for the changing velocities and increasing linewidths observed in this part of the nebula at radio frequencies (Paper I). It also explains the split [N II] lines seen in this vicinity (Deharveng 1973).

Velocity irregularities and line splittings have been seen in the core on size-scales small compared to the flow size. The magnitude of the effect is generally smaller than twice the sound speed, and suggests that these irregularities result from eddies and small substreams caused, perhaps, by neutral globules imbedded in the flow. Globules in the vicinity of the core, such as those studied by Penston (1969), are known to exist.

Finally, we wish to point out that the idea of asymmetric density distributions and flows in Orion A is not new. Wurm (1961), Kaplan and Pikelner (1970), Terzian and Balick (1973), and Zuckerman (1973) have all suggested some of these concepts earlier, both in Orion and elsewhere. Observational evidence for flows can be seen in photographs of simpler H II regions where the identity of flow regions is almost unmistakable (e.g., plate of Horsehead nebula, p. 121 of Lynds 1968). The main contribution of the present model lies in its refinement and synthesis of previous ideas in order to construct a more-detailed model which explains the observational evidence now available.

IV. Theory

Even though the present model has been developed on empirical grounds, some theoretical justification for certain aspects of the model is possible. In the remainder of this section we pursue the theory of the flows and investigate several important implications which develop from the discussion. We shall use N, ρ, v, c, T, and p to represent number density, mass density, velocity, isothermal sound speed, temperature, and pressure in the ionized (H II) and neutral (H I) regions, respectively.

The theory of ionized flows from neutral gas has been studied theoretically by Mendis (1969) and more recently by Dyson (1973). Although these authors invoke some restrictive assumptions concerning the nebular geometry, their conclusions can be expected to be generally valid. To summarize, the flows originate in ionization fronts of the critical or strong D type (for exciting stars as early as θ^1C), and the flow velocity expected will vary between $c(\text{H II}) \leqq v(\text{H II}) \leqq 2c(\text{H II})$, where c is about 10 km s^{-1} to 12 km s^{-1}. The exact velocity depends on the strength of the radiation field at the front and the density of the ambient ionized gas into which the gas flows.

We first investigate the density of the neutral region, N(H I), required to sustain the observed core densities, N(H II), both in the primary flow (N(H II) $\sim 10^{4.5}$ cm^{-3}) and throughout the core (N(H II) $\sim 10^3$ cm^{-3}). Given the assumption of steady flow, it follows that

$$\frac{\text{N(H II)}}{\text{N(H I)}} = \xi \frac{v^2(\text{H I}) + c^2(\text{H I})}{2c^2(\text{H II})} \tag{1}$$

(Spitzer 1968), where v(H I) is the velocity of the ionization front into the neutral gas. Here c is given by $c \sim 0.081\ (\zeta T_e)^{1/2}$ where ζ is unity for neutral gas and 2 for singly ionized gas. Under conditions of interest here, $v(\text{H I}) < c(\text{H I})$ (i.e., D-type ionization fronts), and ξ is of the order unity for $v(\text{H II}) \sim c(\text{H II})$, as observed. Thus

$$\frac{\text{N(H I)}}{\text{N(H II)}} \sim \frac{2c^2(\text{H II})}{c^2(\text{H I})} \sim \frac{4T(\text{H II})}{T(\text{H I})} \tag{2}$$

(note that the pressure in the H II region is twice that in the neutral gas). Thus N(H I) is in the vicinity of $10^{7.5\pm0.5}$ cm^{-3} for $T(\text{H I}) \sim 10^{1.5\pm0.5}$ °K, where T(H I) is inferred from molecular observations (e.g., Solomon 1973). These are very high neutral densities, so it is likely that the primary flow comes from a relatively small dense region of the neutral complex with dimensions similar to the primary flow size ($\lesssim$0.1 pc). Elsewhere in the core, the other weaker flows originate from the neutral complex (Fig. 2) whose ionized gas densities vary nearly proportionally with the local value of N(H I). These weaker flows are probably subsonic. Because of the geometry of the cavity, the primary and secondary flows may "focus" ionized gas near the core center before this gas can disperse. Some of the minor brightness variations in the core around the primary flow may result from this mechanism.

In order to account for the average core density, the surrounding neutral gas must have an average density $\lesssim 10^6$ cm^{-3}, although smaller neutral densities are possible if the primary flow is the dominant source of ionized gas in the core. Note that $\langle N(\mathrm{H\,I})\rangle \gtrsim 10^{5\pm1}$ cm^{-3} is indicated by radio observations of lines formed in the nearby neutral complex (§V of Paper I).

It is also possible to estimate the mass inflow rate for the core given by

$$\frac{dM(\mathrm{H\,II})}{dt} = mN(\mathrm{H\,I})v(\mathrm{H\,I})\,A \quad , \qquad (3)$$

where m is the average mass per particle ~ 1.4 times the proton mass, and A is the cross-sectional area through the flow. We use the equation of flow continuity at the ionization front, $\rho v =$ constant, and make use of the observed density and velocity in the H II region, $N(\mathrm{H\,II}) \sim 10^{4.5}$ cm^{-3} and $v(\mathrm{H\,II}) \sim 10$ km s^{-1}. A is of the order of $\sim 10^{35}$ cm^2. Then we find a mass inflow rate of about $10^{-4}\,\mathfrak{M}_\odot$ yr^{-1}. Flows from the remainder of the core will have a comparable effect. Given that the mass of the core and surrounding H II region is $\sim 10\,\mathfrak{M}_\odot$ and that the free expansion relaxation time of this peaked density distribution is 60,000 years (Vandervoort 1963), it follows that the mass inflow rate of $\sim 10^{-4}\,\mathfrak{M}_\odot$ yr^{-1} can sustain the presently observed density distribution in an equilibrium configuration. Furthermore, because many tens of thousands of solar masses of neutral material exist nearby (C. P. Gordon 1970; Tucker, Kutner, and Thaddeus 1973), this configuration can be maintained over times long compared to the relaxation time. Therefore, we suggest that the Orion nebula may be older than estimates based on its relaxation time imply, and could possibly be consistent with the stellar cluster age of more than 10^6 yr (Penston 1973).

V. Other Observations and Previous Interpretations

We now explore the interpretation of previous observations in further detail. In the course of the discussion we refine the model presented earlier and discuss some earlier models for the core structure. The data to be discussed cover a wide range of topics with little logical connection; consequently this section is divided into several subsections.

A. *Specific Features.* The photographs, Plates II, III, and IV, of the core region show a number of specific interesting features. The brightest of these corresponds to the primary flow already discussed above. Another prominent emission feature is the bright filament located about 1′ SE of the Trapezium (Plates III and IV). This filament does not appear as a prominent feature in the radio-synthesis map; however, its inconspicuousness is at least partially attributable to the perpendicular orientation of the elongated beam synthesized by Webster and Altenhoff (1970). An increase in neutral density on the far side of the filament from θ^1C is suggested by a map of the ^{13}CO distribution which shows a sharp rise behind the filament (Solomon 1973). It is therefore tempting to suggest that the filament is a weak flow from an ionization front seen edge on. The color photograph of the core from Lick Observatory (recently reproduced on the cover of the March 1973 issue of *Physics Today*) is interesting in this regard. The filament appears somewhat green on the side of the filament facing θ^1C and red on the opposite side; this might be explained by the appearance of the strong red lines of low ionization species such as [O II], [N II], and [S II] near the neutral gas and the strong green line of [O III] in the ionization front adjacent to the H II region. Careful studies of several optical lines near the filament are planned.

Another interesting feature is an intensity minimum or "trough" located between the filament and the Trapezium. Both the Hα interferograms of Fisher and Williamson, and the [O III] studies of Wilson et al. show the presence of gas in this region with a mottled appearance covering a wide range of velocities. We suggest that along the line of sight through the trough lies a region in which gas is dispersing from the primary flow and perhaps interacting with a weak flow from the filament. Also, to the SE of the filament lie the θ^2 stars and a small nebulosity close to θ^2A just behind the filament. These features are probably not physically related to the core region.

The radio-synthesis map shows a minor peak located on the edge of the dark bay nearest the Trapezium. It is not clear from the map that this source is distinct from the brightest radio source associated with the primary flow to which the radio contours are connected. This source may be a part of the primary flow which is occulted by the dark bay.

B. *Linewidths.* The widths of various lines in Orion have been a subject of some interest. Early radio measurements indicated the hydrogen lines were broadened by supersonic turbulence (e.g., Mezger and Höglund 1967); however, Weedman (1966) shows that the interpretation of radio-line observations of poor spatial resolution was confused by mass motions within the core (as seen in lines of [O III] by Wilson et al. 1959). Later, Smith and Weedman (1970) measured the widths of optical forbidden lines with 10″ spatial resolution in the vicinity of the primary flow and found the turbulence to be subsonic with turbulent velocities of 7–10 km s^{-1}. These values do not conflict with the present model provided gas disperses subsonically from the primary flow.

We wish to point out that as observations have improved at both optical and radio frequencies, no evidence of large-scale multi-velocity gas components in the core of Orion has been established. For example, the widths of radio lines observed with moderate spatial resolution ($\sim 3'$) show the linewidths to be remarkably constant over the nebula (Paper I) with little, if any suggestion of asymmetric line profiles. Much the same applies to the optical lines (Meaburn 1971). This means that any model for the core must be able to explain both the constant linewidths and regular line profiles as well as the velocity changes observed in the core region. In particular, it is easy to exclude the possibility of spherically symmetric rotating or expanding models, as we shall discuss next.

C. *Ionized Gas Velocities.* We have already reviewed much of the information obtained from line velocities inside the H II region. Based on the distribution of forbidden-line velocities Wilson et al. (1959) and Deharveng (1973) have postulated that the core consists of a symmetric sphere expanding at 10 km s^{-1} near the center whose far side is hidden optically because of obscuration. However, Weedman (1966) pointed out that the close agreement between the optical [O III] and radio H II velocities and linewidths (at radio wavelengths where the nebula is optically thin) means that the far side of this hypothetical expanding sphere could not exist. More recently Batchelor and Brocklehurst (1972) have reproposed the expanding-sphere model to account for the increasing approach velocities of hydrogen recombination lines that are seen at lower radio frequencies where the inner portion of the core becomes optically thick. Their models differ from that proposed by Wilson et al. (1959) in that the expansion takes place over much larger scale sizes so that only the tenuous gas outside the core is observably affected. This low-density gas contributes unnoticeably to line emission observed at frequencies where the nebula is optically thin and emission from the core dominates. At lower frequencies the core becomes opaque and the blue-shifted foreground gas dominates the line emission. Notice, however, that the corresponding hypothetical tenuous background gas never influences the line radiation and need not exist to explain the line velocities.

In the flow model discussed here the same observations are explained by gas driven outwards and expanding freely from the nebular core toward the observer. The asymmetry of the nebular geometry makes it unlikely that the unobserved receding component suggested by Batchelor and Brocklehurst exists. Unlike the spherical models, the present model provides an interpretation for the change in velocity with line excitation observed optically due to the acceleration of gas through the ionization front behind the flow (Kaler, 1967; see also discussion above). It also explains the H II–C II systemic velocity difference and the very narrow optical linewidths which cannot be adequately understood by a model of spherically symmetric expansion.

Maps of the hydrogen and helium recombination lines (Paper I and references therein) show a velocity gradient approaching ~ 1 km s^{-1} arc min^{-1} from west to east. A model of a rotating core has been inferred from the gradient (Mezger and Ellis 1968; Gordon and Meeks 1967). However, the constant linewidths observed throughout the core do not support such a model. Furthermore, a careful examination of the velocity differences between the H II and C II lines shows that the eastern edge of the "rotating" core is fixed relative to the neutral gas nearby whereas the center of the core is moving away from the neutral gas toward the observer. A mechanism which might account for this strange rotational configuration has not been suggested. In the present model the H II–C II velocity differences in the core have been explained by the system of flows as described in section III.

To explain the velocity differences between the ionized and neutral gas, Menon (1967) suggested that the entire H II region is receding from the neutral gas and the exciting star θ^1C toward the earth. This interpretation of the data implies that the neutral and ionized gases are entirely decoupled and furthermore requires a mechanism for explaining the velocity differences between the regions. Such a neutral-ionized gas configuration is not seen in other H II regions. We feel Menon's model is unlikely.

Finally, we wish to comment on optical line splittings observed by several groups. These splittings fall into two categories; i.e., those with subsonic and those with supersonic velocity differences. The subsonic splittings were explained in section III as eddies and substreams of the primary flow. On the other hand, the supersonic splittings are rather controversial, and no two sets of observers have measured consistent velocities (e.g., Lee 1969; Meaburn 1971; Fisher and Williamson 1970; Dopita et al. 1973). An explanation for these velocity components, if indeed they exist, lies beyond the scope of the present model.

VI. The Neutral Gas Near Orion A

We have proposed a model for the region near Orion A in which the ionized nebula is imbedded in the near side of a much more massive cloud of neutral gas. In this section this neutral region is described in greater detail. A model is proposed in which the neutral cloud is gravitationally contracting towards its dynamical center located in the Kleinman-Low (K-L) infrared nebula. The evolution of this system is considered at the end of this section.

The existence of a massive cloud of neutral gas lying behind the H II region Orion A is well established (Kutner and Thaddeus 1971). The mass of this cloud within 2′ (0.25 pc) of the K-L nebula has been estimated to be at least $10^3\ \mathfrak{M}_\odot$ but probably less than $2 \times 10^4\ \mathfrak{M}_\odot$ (Zuckerman 1973). This mass is at least two orders of magnitude greater than the combined mass of the ionized gas and associated stars in the H II region (Schraml and Mezger 1969; Penston 1973). Consequently, the ionized nebula has little effect on the dynamical evolution of the neutral cloud.

Using the Jean's criterion in the form adopted by Larson (1969*a*), one finds that the Jean's radius for a cloud of molecular hydrogen of mass $\mathfrak{M} \sim 10^3\ \mathfrak{M}_\odot$ at a kinetic temperature $T_{\rm kin} \sim 30°$ K is $r \sim 40$ pc, so that the observed cloud ($r \lesssim 0.3$ pc) is certainly undergoing gravitational contraction. The gravitational collapse of a cloud proceeds in a nonhomologous manner with isothermal outer regions and a nearly adiabatically contracting core. In theoretical models of spherical protostellar contraction, the density ($n_{\rm H_2}$) and collapse velocity ($V_{\rm coll}$) in the outer isothermal regions are found to have the form (Larson 1969*a*,*b*; Hunter 1968; Larson and Starrfield 1971)

$$n_{\rm H_2} \propto r^{-2} \qquad (4)$$

and

$$V_{\rm coll} \propto r \quad . \qquad (5)$$

The quasi-adiabatic contraction of the optically thick core has the form (Larson 1972*a*,*b*; Larson and Starrfield 1971)

$$n_{\rm H_2} \propto r^{-3/2} \qquad (6)$$

$$V_{\rm coll} \propto r^{-1/2} \qquad (7)$$

$$T \propto r^{-1/2} \quad , \qquad (8)$$

where T is the temperature of the gas. These core conditions propagate radially outward with the free-fall time scale into the outer, more slowly contracting part of the cloud where the isothermal conditions (eqs. (4) and (5)) still apply. The isothermal contraction proceeds according to equations (4) and (5) for most of the cloud outside the adiabatically collapsing core. The later development of the core is dependent on the initial cloud mass, whereas the isothermally contracting regions evolve the same way independent of the initial mass.

Heiles (1973) has suggested that the isothermal conditions describe the contracting molecular cloud behind Orion A. He has shown that the observed molecular linewidths may be explained by mass motion (i.e., gravitational contraction) rather than supersonic turbulence ($\Delta V \propto V \propto r \propto n_{H_2}{}^{-1/2}$), so that lines collisionally excited at lower neutral density are observed to be systematically broader than high-excitation lines. We now suggest that this linear dependence of collapse velocity on radius, for an isothermal cloud, is directly observable in the Orion A molecular cloud.

In the following discussion, we refer to Figure 3, in which the observed radial dependence of velocity and density in a line of sight passing through the center of the Orion A molecular cloud is compared with the radial dependences expected from equations (4) and (5). At the center of the molecular cloud is located the Kleinman-Low infrared nebula ($r < 10^{17}$ cm, $n_{H_2} \gtrsim 10^7$ cm^{-3}), containing the H_2O and OH point sources ($r \sim 10^{14}$–10^{15} cm) of maser emission as well as intense far-infrared emission. Surrounding the K-L core is the dense molecular cloud ($10^{17} < r < 10^{18}$ cm, $\langle n_{H_2} \rangle \sim 2 \times 10^5$ cm^{-3}) observed as a more-extended source. (The asymmetry and possible rotation of this cloud will not be considered in this very crude picture.) The Orion A H II region is

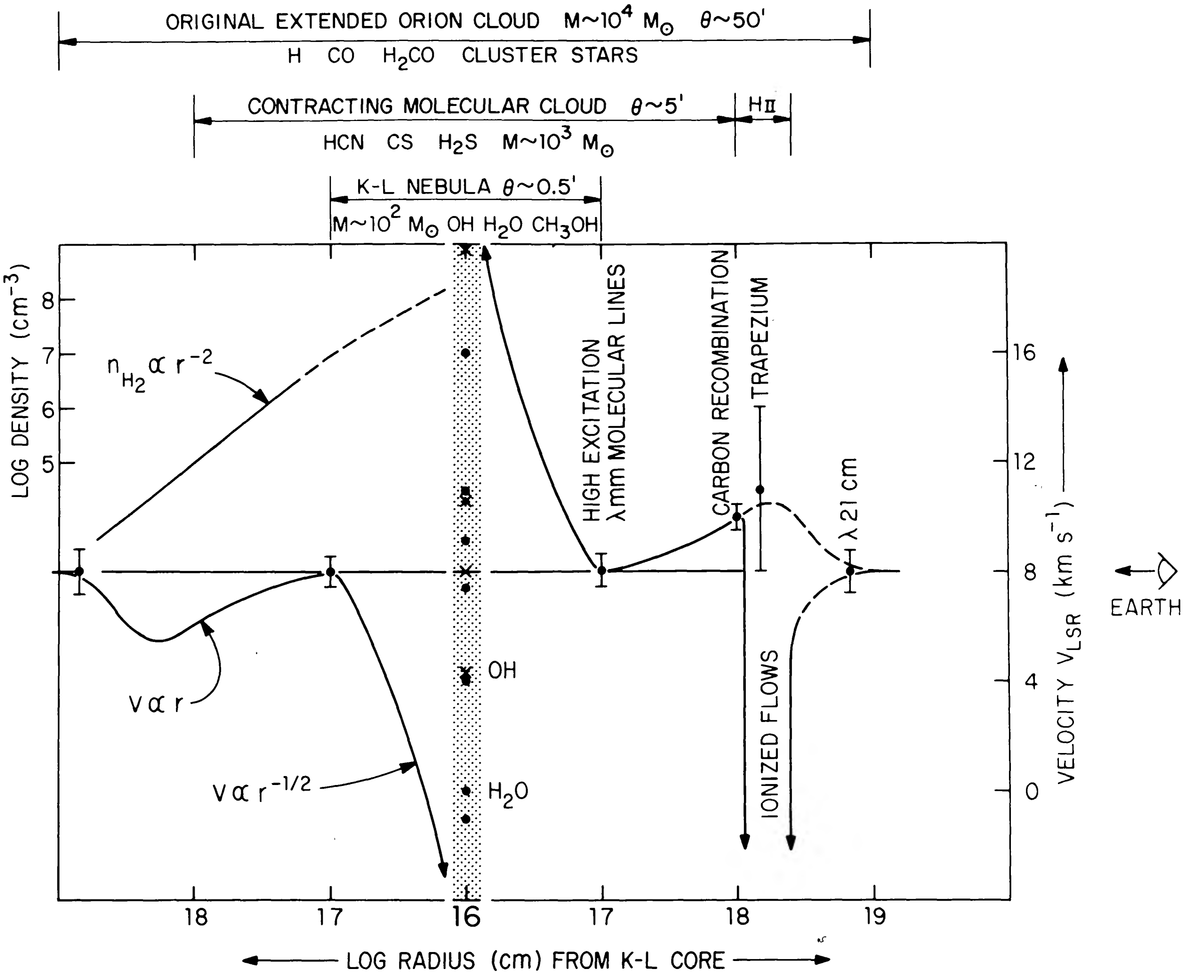

FIG. 3 — A schematic diagram illustrating the radial dependence of velocity and density along a line of sight passing through the center of the Orion molecular cloud which coincides with the Kleinman-Low infrared nebula. The assumed spherical symmetry of this idealized model for the neutral gas cloud results in symmetric velocity and density profiles about the K-L core, except for the perturbing effect of the H II region imbedded in the near side of the molecular cloud. Representative observed velocities include: the OH and H_2O masers within the adiabatically contracting molecular core ($V_{LSR} \simeq -5$ to $+20$ km s^{-1}), the high-excitation millimeter wavelength molecular lines ($V_{LSR} \simeq +8$ km s^{-1}), the carbon recombination lines at the H I–H II interface ($V_{LSR} \simeq +10$ km s^{-1}), and the λ21 cm emission from the original extended neutral gas cloud ($V_{LSR} \simeq +8$ km s^{-1}).

located on the near side of this dense molecular cloud, about 0.3 pc from the cloud core. Surrounding the molecular cloud is the more tenuous and extended region of neutral gas ($10^{18} < r < 10^{19}$, $\langle n_{H_2} \rangle \sim 2 \times 10^3$ cm^{-3}), out of which both the molecular cloud and K-L core have contracted. The stars of the Orion cluster define the projected boundary of this extended cloud (diameter $\sim 1°$).

In the present model, the adiabatic core conditions are considered applicable to the K-L nebula, while the molecular cloud seen at mm wavelengths is considered to be in the isothermal phase of contraction. The isothermal conditions probably extend into the more tenuous surrounding neutral gas which is taking part in the contraction ($r < 10^{19}$ cm).

Now consider the run of velocity with radial distance in the line of sight through the center of the cloud. The condensed core of the Orion A molecular cloud, as defined by the K-L nebula ($r \sim 10^{17}$), is observed to be at rest with respect to the more tenuous and extended neutral gas cloud in the general Orion region ($10^{18} < r < 10^{19}$ cm). The peak velocity of the atomic hydrogen cloud within 20′ of Orion A is $V_{LRS} \sim 8$ km s^{-1} (Gordon 1970; Radhakrishnan et al. 1972). The velocity of the core of the molecular cloud is now well determined ($V_{LSR} \simeq 8.0 \pm 0.5$ km s^{-1}) from various observations of molecular emission lines at mm wavelengths, in particular those lines which require the high-excitation conditions ($T_{KIN} \geqq 70°$ K, $n_{H_2} > 10^6$ cm^{-3}) available only within the core of the molecular cloud. Of these high-excitation and/or optically thin transitions, the most accurately determined velocities include: the set of five CH_3OH lines at 25 GHz, $\langle V_{LSR} \rangle = 8.0 \pm 0.5$ km s^{-1} (Barrett, Schwartz, and Waters 1971), $V_{LSR} = 8.2 \pm 0.3$ km s^{-1}, (Chui et al. 1974); the set of eight CH_3OH lines at 145 GHz, $V_{LSR} = 7.5$ km s^{-1} (Kutner et al. 1973); the $J = 7 \rightarrow 6$ OCS line, $V_{LSR} \simeq 7.5 \pm 0.5$ km s^{-1} (Turner 1974); and the 1_{10}–1_{01} line of H_2S, $V_{LSR} = 8.2 \pm 0.5$ km s^{-1} (Thaddeus et al. 1972). (For reviews of molecular velocities in Orion, see Zuckerman and Ball 1974.) Although thermal molecular emission from regions much smaller than $r \sim 10^{17}$ cm ($\theta \sim 30''$) suffers serious beam dilution at the current resolution of single-dish, mm-wavelength telescopes, the numerous H_2O and OH maser sources within the K-L nebula have been resolved by VLBI methods. Although VLBI observations reveal a complex spatial and velocity structure of the OH and H_2O emission in Orion A, only for the center of the Kleinman-Low nebula is there close agreement of OH and H_2O features in both position and velocity (V_{LSR} (OH) $= +7.6$ km s^{-1}, Raimond and Eliasson 1968, V_{LSR} (H_2O) $= 7.9$ km s^{-1}, Hills et al. 1972 and Moran et al. 1973).

We mention in passing that the lines of H I, OH, and H_2CO seen in absorption against the Orion A continuum at somewhat lower velocities are less useful in the present context, as the associated foreground gas bears an uncertain physical relationship to the contracting molecular cloud under discussion. The same caution may apply to the low-frequency carbon recombination lines which may be formed by stimulated emission processes (Dupree 1974; Paper I; Zuckerman and Ball 1974).

For an isothermal collapse velocity which increases with increasing radial distance from the core, one expects the neutral gas at the near edge of the molecular cloud ($r \sim 10^{18}$ cm) in the line of sight to the core to show a greater positive velocity than the core (Fig. 3). This expectation is confirmed by the recent observations of the C85α and C110α recombination line emission at $V_{LSR} \simeq +9.7 \pm 0.5$ km s^{-1} from the edge of the molecular cloud exposed to the H II region (Paper I and Fig. 3). Carbon recombination lines are especially useful for defining the velocity of the neutral gas at the H I–H II interface, which in the present model is the most positive velocity observable in the neutral gas outside the K-L core (see Fig. 3). Interpretation of the velocities of the low-excitation and/or optically thick molecular emission lines of CO and CS is more difficult, but the intermediate velocities observed ($V_{LSR} \simeq 9.0 \pm 0.5$ km s^{-1} for $J = 1 \rightarrow 0$ ^{12}CO and ^{13}CO, ^{12}CS, and ^{12}C^{34}S, Liszt et al. (1974)) are expected in the present model for lines formed at intermediate depths into the molecular cloud ($r \sim 10^{17}$–10^{18} cm).

From the observed velocity difference between the K-L core ($V_{LSR} \simeq 8.0 \pm 0.5$ km s^{-1} for $r \lesssim 10^{17}$ cm) and the H I–H II boundary ($V_{LSR} \simeq 9.7 \pm 0.5$ km s^{-1} at $r \sim 10^{18}$ cm) the application of equations (4) and (5) with the assumption of spherical symmetry in the molecular cloud leads to a radial gradient of $\Delta V/\Delta r \sim 6 \pm 3$ km s^{-1} pc^{-1} for the region of the molecular cloud $10^{17} < r < 10^{18}$ cm. (Liszt et al. (1974) have stressed the importance of radial mass motions in the Orion molecular cloud and suggest a gradient of $V/r \sim$ 2–8 km s^{-1} pc^{-1} as appropriate to their measured CO and CS transitions.) If, as Heiles (1973) suggests, the molecular linewidths in Orion are dominated by collapse motion rather than by turbulence, then for optically thin, high-excitation ($n_{H_2} > 10^5$ cm^{-3}) lines formed over the full path length (0.5 pc) through the molecular cloud, the velocity gradient derived above ($\sim$6 km s^{-1} pc^{-1}) leads to expected linewidths of order $\Delta V \sim 3$ km s^{-1}, in good agreement with the observed widths. The broad ($\Delta V \simeq$ 15–20 km s^{-1}) wings of molecular lines (e.g. SiO, HCN) observed at high spatial resolution ($\theta_B \sim 1'$) toward the K-L position probably represent the much higher collapse velocity ($V \propto r^{-1/2}$) of gas in the free-falling molecular core (Fig. 3). These broad wings are comparable to the spread in observed velocities of H_2O and OH maser emission, $V \simeq -7$ to $+24$ km s^{-1}, about a mean velocity of $V \simeq 8$ km s^{-1} (Turner 1974).

Referring again to Figure 3, the model of isothermal contraction for the cloud external to the K-L core is further supported by the reasonableness of a density distribution which falls off as r^{-2} from the edge of the K-L nebula ($r \sim 10^{17}$ cm, $n_{H_2} \sim 10^7$ cm^{-3}) out to the boundary of the CO emission ($r \sim 10^{19}$ cm, $n_{H_2} \sim 10^3$ cm^{-3}). This r^{-2} radial-density dependence is more consistent with the collisional excitation requirements of each molecular species observed and its corresponding angular extent than is an $r^{-3/2}$ dependence.

We conclude this section on the neutral gas with a comment on the coupled evolution of the Orion gas cloud and cluster stars.

The stars in the Orion cluster are distributed over roughly the same projected one-square-degree area of sky within which the λ2.6 mm emission from CO is observed (Liszt et al. 1974). This agreement is expected since the minimum density ($n_{H_2} > 10^3$ cm^{-3}) required to produce detectable CO emission is comparable to the minimum density considered necessary to ensure star formation via protostellar gravitational contraction (Larson 1969*a,b*). The free-fall time ($\tau \sim 10^7$ yrs) of the extended Orion cloud ($r \sim 10^{19}$ cm, $n_{H_2} \sim 10^3$) agrees well with the age of the Orion cluster ($\tau \sim 10^{6.8}$ yrs, Penston 1973), which suggests that star formation and cloud contraction began nearly simultaneously, long before the current Orion nebula or Trapezium stars existed. One might then expect that cluster stars which have formed more recently from the denser, more rapidly collapsing gas will appear systematically redshifted. Johnson (1965) has found just such an apparent effect in the Orion cluster stars, a dependence of stellar velocity on spectral type, in the sense that the youngest, most-massive stars have the highest positive velocities. In particular, the center-of-mass motion of the Trapezium stars should approximate the infalling motion of the gas out of which these stars formed. The measured average velocity of the four Trapezium stars is $\langle V_{LSR} \rangle \simeq +11$ km s^{-1} (Johnson 1965). A linear velocity gradient of 6 km s^{-1} pc^{-1} would then place the Trapezium stars at a distance of $\sim$0.5 pc from the K-L core, and roughly in the center of the H II region carved out of the neutral gas (see Plate IV of this paper and Fig. 1 of Zuckerman 1973). It is also interesting that the highest-velocity ionized gas ($V_{LSR} \sim 10 \pm 2$ km s^{-1}) observed in the optical studies of [O II] and [O III] emission (Münch and Wilson 1962; Fischel and Feibelman 1973) is centered on the exciting star θ^1C and agrees with the velocity of the neutral gas at the H I–H II interface as measured in C^+. This supports the present picture of the radiation from the Trapezium stars eating into the dense neutral gas. Hence the dynamical evolution of the H II region depends strongly on the progress of the Trapezium stars as they fall toward the center of the molecular cloud.

VII. Flows in Other H II Regions

We consider the possibility that the flow model can be extended to explain the radio fine structure observed in other H II regions. This possibility is suggested by the many morphological similarities seen in other nebulae containing fine structure. The principal similarities are the dynamic activity observed in these nebulae as determined by their complex line shapes and systematic H II–C II velocity differences; the association of large, dense, neutral regions and dust nearby; the central location of the fine structures at the density peaks of the compact density components (as observed by Schraml and Mezger 1969, and others); and the similar densities, excitations, and size scales for the small radio structure (as discussed by Balick 1972, and Wynn-Williams and Becklin 1973).

However there is one major difference between the radio structure seen in Orion A and the radio structure in other nebulae. This difference is that no prominent infrared emission source is coincident with the Orion structure at any infrared wavelength, whereas the infrared luminosities of structures in other H II regions is at least comparable to the ultraviolet luminosity required to explain the nebular excitation (Wynn-Williams and Becklin 1973). That is not to say that dust is absent in the primary flow; the presence of dust inside the nebula and its distribution has been discussed by O'Dell and Hubbard (1965), Münch and Persson (1971), Mathis (1970), and others.

The general consensus at present is that protostellar H II regions are the explanation for regions where bright radio and infrared structure is coincident. This may often be the case, but such a model fails to explain the strong dynamic activity observed in these nebulae. We feel quite certain that the radio structure in Orion A is associated with strong flows and, furthermore, the existence of flows in other nebulae is not only necessary to explain the dynamic activity, but also inevitable since the placement of dense neutral material near a strong source of ultraviolet excitation will be a common occurrence. Therefore, we caution that flows in these nebulae may have been overlooked, perhaps because of observational effects (e.g., their brightness is less than that of the protostellar H II regions).

There is also an alternate explanation for these "protostellar H II regions" which involves flows. It may be that in many cases, the observed radio emission does not arise in an interior H II region in these protostellar clouds, but rather results from an exterior flow. The possibility of ionized "jackets" has been explored theoretically most recently by Dyson (1973). The infrared source is still explained by heated dust in the interior of the collapsing cloud. The principal objection to such a model involves the substantial ultraviolet excitation necessary to explain the radio flux which, because of geometric dilution, is most easily explained by an interior source of excitation. This does not exclude the possibility of exterior exciting stars imbedded in the flows.

At least two experiments are suggested to investigate the nature of the small-scale radio structure, both in Orion A and elsewhere. The first of these involves the accurate determination of the relative positions and sizes of the radio and infrared structure. The second is a high spatial resolution mapping of radio recombination lines in order to study the role of flows. Optical velocity studies would also be interesting, but these are hampered by the nearly total obscuration associated with the small structure, with the best-known exception being Orion A.

VIII. Conclusions

In this paper we have discussed the structure of the ionized nebula and neutral complex near Orion A. The nebular model is a highly dynamic one where newly ionized gas flows into the nebular core from the nearby neutral gas, and then disperses into the lower density medium on the near side of the neutral complex. We have found that the small-scale structure seen in Orion A can be adequately explained, not as protostellar H II regions, but as high-density ionized gas flowing more or less along the line of sight. The details of the flow pattern are not known and are probably quite complex. Gas in the flow expands into the nearby medium through channels in the neutral gas and accounts for the weaker "swirling" gas seen several arc minutes west of the core.

The neutral complex is undergoing large-scale gravitational contraction, and the Kleinman-Low nebula (located at the dynamical center) is a site of star formation. The Trapezium stars are falling toward the neutral complex and their present proximity is responsible for the dynamically active H II region.

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