THE ASTROPHYSICAL JOURNAL, 269:164–174, 1983 June 1

A STUDY OF Hα VELOCITIES IN NGC 1499, NGC 7000, AND IC 1318B/C

W. F. FOUNTAIN, G. A. GARY, AND C. R. O'DELL
George C. Marshall Space Flight Center, NASA
Received 1982 July 2; accepted 1982 November 15

ABSTRACT

Multiple slit echelle spectrograph observations of the Hα emission line are used to map the radial velocities of the California Nebula (NGC 1499), the North American Nebula complex (NGC 7000 and IC 5070), and IC 1318B/C. The California Nebula is singularly constant in velocity, considering its geometry. The North American Nebula complex reflects a very simple, classical dynamical picture. The expansion discovered earlier in IC 1318B/C is confirmed, detailed, and the model refined. The new data, along with that in earlier papers of this series, show that stellar wind acceleration and champagne flow mechanisms both play important roles in determining the evolution of H II regions.

Subject headings: nebulae: H II regions — nebulae: individual

I. INTRODUCTION

A review paper of 14 years ago (Mathews and O'Dell 1969) on the evolution of H II regions reported that all was well, that we understood the basic processes occurring in diffuse nebulae, and that we knew how these ubiquitous objects change with time. To be sure, there were a few open questions, but the picture appeared consistent and basically complete. The situation now is one of much greater uncertainty because of advances in theory and observation. We now know that theoretical models having the photoionizing stars offset from the center of the original neutral cloud can have a very different and shorter evolution than the traditional, symmetric models. Ultraviolet observations of young, luminous stars (Snow and Morton 1976) have demonstrated a sizable stellar wind of hot plasma, and theory has shown that this wind can have significant effect on the dynamics of a surrounding nebula. Finally, a series of reliable observational investigations has shown that supersonic velocities are common features of nebulae, contrary to the expectations of early theory. This paper is the third of a series (Fountain, Gary, and O'Dell 1979; Mufson *et al.* 1981) reporting on detailed studies of the velocity structures in H II regions. This work extends and complements earlier investigations made by other observing methods.

Our investigation has been directed toward three nebular regions, each possessing a different basic structure from the others and the two nebulae investigated earlier. By means of a velocity analysis of the Hα emission across the face of the nebulae, we hoped to accurately model and understand the structure and evolution of these regions. The new data have allowed us to distinguish between dynamically very different objects in which quite different processes dominate. In § II we describe the new observational material, in § III the relevant theoretical work, in § IV the models that we derive, and in § V we discuss the results for the five nebulae that have been studied.

II. OBSERVATIONS

The method of observation used in this study was essentially identical to that used previously for studies of the Rosette Nebula (Fountain, Gary, and O'Dell 1979) and NGC 6611 (Mufson *et al.* 1981). The multi-entrance slit, siderostat-fed echelle spectrograph produces stigmatic images in the hydrogen Hα emission line. The spectra were calibrated in terms of full width at half-maximum (FWHM) intensity and radial velocity by means of an internal calibration source. The spectrographic plates were scanned by a Perkin-Elmer PDS Micro-10 microdensitometer and converted to relative intensity units. The method of guiding and field rotation meant that the same area was often covered on several different data plates. We have averaged and presented the results for areas 5′ in declination by 0ᵐ.5 of right ascension.

The individual line profiles were analyzed for two observational parameters, the FWHM and the radial velocity. All line profiles were submitted to a least squares fit to a Gaussian function. Lines that were suspected of not being single were fit to two Gaussians of selectable intensity ratio but equal individual FWHM.

In order to make the presentation clearer, the same format and order will be used for each region. Since there is an abundance of data to be presented, each section begins with a description of the optical appearance of the region. The red plate of the Palomar Observatory Sky Survey (POSS) was used to derive Hα + [N II] intensity which is also shown on the plots of data. The intensity values, which are dominated by Hα, were used together with the number of spectra falling in a particular spatial bin to determine the relative confidence of the results. The larger, darker entries indicate greater reliability. The radial velocity data are presented graphically and then the FWHM values in a similar format. In the event that the lines were compound, the results of a double Gaussian fit for those lines are also given. Other similar and related observations are discussed in § IV.

a) NGC 1499

The observations of NGC 1499 (the California Nebula) show that no significant variation in radial velocity is present (Fig. 1) and there is only a small variation in the FWHM (Fig. 2). The mean heliocentric radial velocity is $+0.5 \pm 4.0$ km s^{-1} (probable errors are used throughout), and the mean FWHM is 26.8 $\pm$ 0.6 km s^{-1}. The radial velocity value is to be compared with +3.2 (Miller 1968) and +6.6 (Courtes, Cruvellier, and Georgelin 1966) derived from Hα measurements at fewer points. The $H_{166\alpha}$ radio line velocities of Pedlar (1980) agree with our individual region values to ± 1 km s^{-1}. The FWHM result is similar to that given by Courtes, Louise, and Monnet (1968) of 25.1 km s^{-1} for the nebula as a whole.

b) NGC 7000

The extensive NGC 7000 (North American Nebula) complex contains both the named object and the nearby object IC 5070 (Pelican Nebula), the two components being separated by the dark cloud L1630 (Lynds 1962). The radial velocities show only a few variations across the face of the nebula (Fig. 3). The FWHM plot (Fig. 4) shows a uniformity of values except for well-defined large values for a few small regions and for lower values near the "Gulf of Mexico."

The mean value of the heliocentric radial velocity of the complex is -15.1 ± 5.5 km s^{-1}, and the FWHM mean value is 28.6 ± 0.6 km s^{-1}. The mean heliocentric radial velocity for NGC 7000 alone is -15.4 ± 3.7 km s^{-1} and -14.8 ± 4.1 km s^{-1} for IC 5070 alone. The extensive Hα observations of Hippelein (1973) gave heliocentric radial velocities of −15.7 and −16.4 for NGC 7000 and IC 5070, respectively, while Pedlar and Mathews (1973) broad-beam $H_{166\alpha}$ radio observations gave −16.8 km s^{-1} for the complex. A set of Hα observations by Louise and Monnet (1969) of NGC 7000 have a FWHM of 25.1 km s^{-1} (Dyson and Meaburn 1970), and $H_{166\alpha}$ measures (Pedlar and Mathews 1973) give 23.3 km s^{-1} over the complex and a maximum of 28.7 in IC 5070. Our FWHM mean for IC 5070 alone is 37.8 ± 12.7 km s^{-1}. A CO study by Bally and Scoville (1980) indicates line splitting in IC 5070 of about 8 km s^{-1}, which could relate to the larger FWHM seen in Hα.

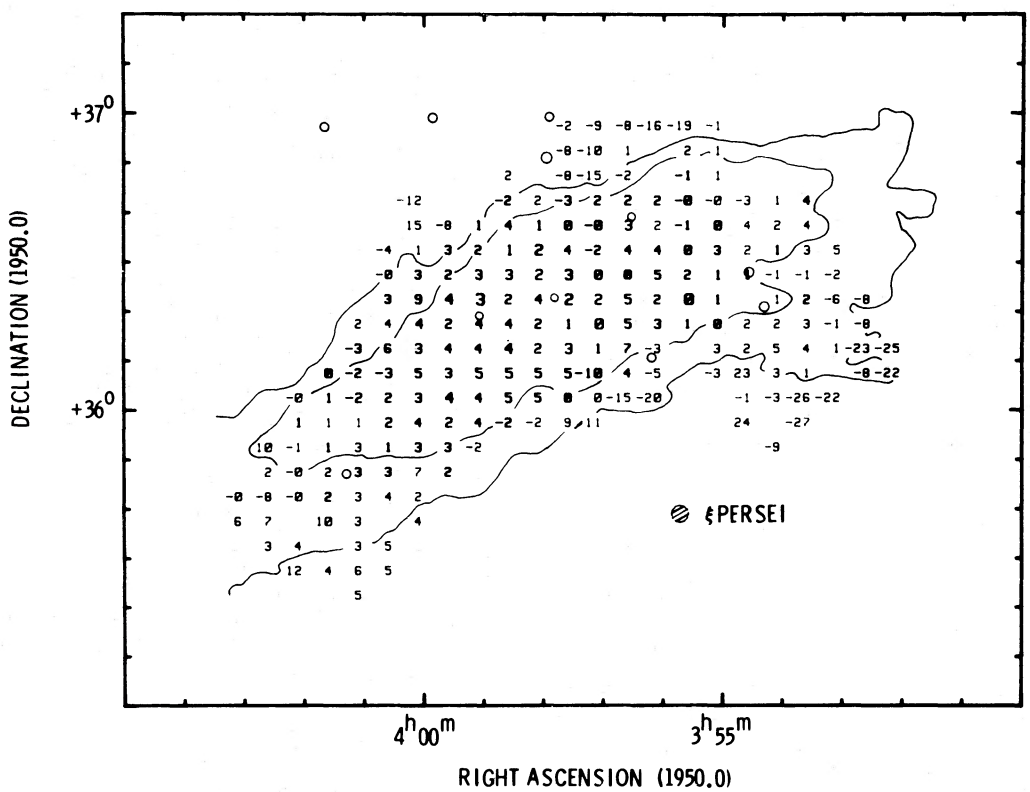

FIG. 1.—Averaged values of the heliocentric velocities (km s^{-1}) are given for various positions in the California Nebula (NGC 1499). Increasing reliability of the data is indicated by increasingly larger and darker print. Circles designate star positions and illustrative isointensity contours are shown.

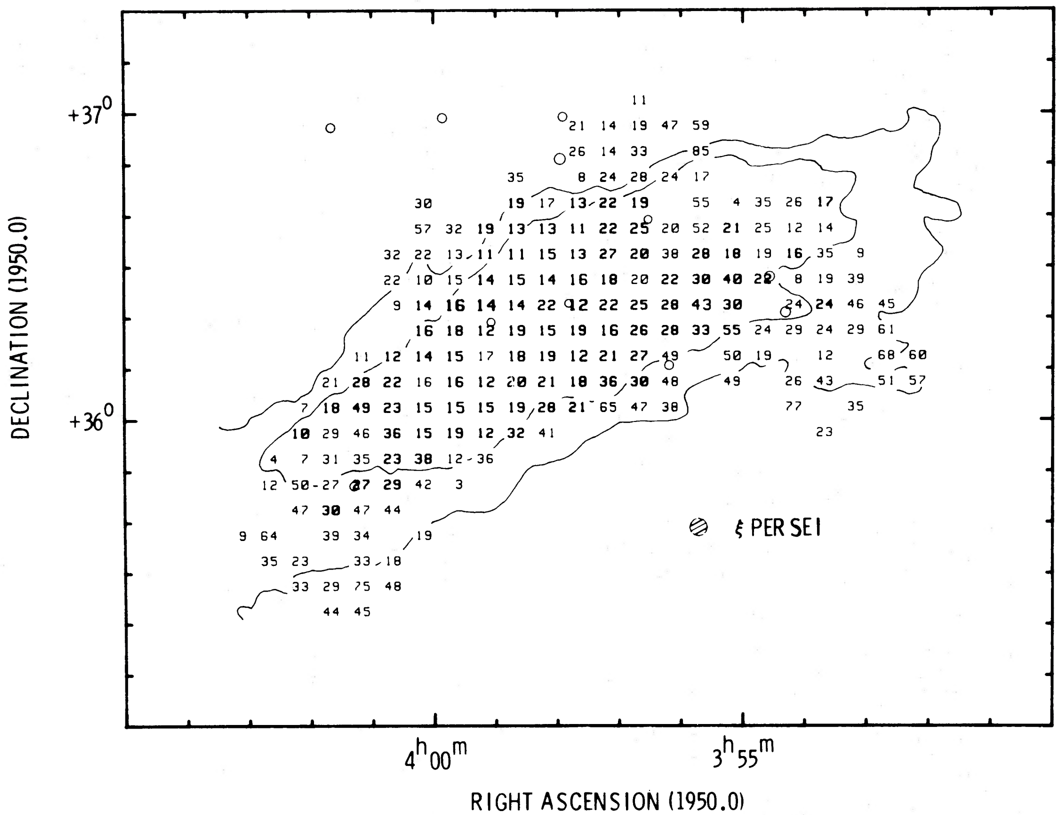

FIG. 2.—The same as Fig. 1 except averaged values of the FWHM are shown

c) *IC 1318B/C*

The two bright emission line nebulosities IC 1318B and IC 1318C are divided by the dark lane L889 (Lynds 1962) and are well separated from IC 1318A. IC 1318B/C appears in the same part of the sky as the Cygnus X supernova source (Goudis 1976), but a relationship has not been established. Splitting of the [N II] lines detected by Goudis *et al.* (1978) made this an interesting region to investigate, especially since the Hα observations of Hippelein (1973) did not show a line separation.

The heliocentric radial velocities for single Gaussian fits are shown in Figure 5 and for those regions with double Hα lines in Figures 6*a* and 6*b*. The separations of the two component regions are shown in Figure 7. Variations of velocity across the nebula are clearly seen. Our values agree to within ± 2 km s^{-1} with the high-intensity regions studied by Canto *et al.* (1979) in [N II], while there is a discrepancy of 10 km s^{-1} with the data of Hippelein (1973). Our mean values are -17.9 ± 5.7 km s^{-1} for IC 1318C, -16.7 ± 4.7 for the unresolved lines on IC 1318B, and -5.0 ± 3.7 and -43.2 ± 5.2 for the two components of the split lines in IC 1318B. The FWHM data are more difficult to present. IC 1318C emission is adequately fit by a single Gaussian profile line, but with a width of 52.5 ± 13.1 km s^{-1}, which is much broader than the other nebulae studied. The interpretation of this will be covered in § IV. The results of fitting all of the regions to single Gaussian fits are shown in Figure 8. The FWHM values in Figure 8 for regions shown in Figures 6 and 7 to have split lines are strictly formal. In the split line regions it was assumed that the FWHM of the individual components was 23 km s^{-1} (Goudis *et al.* 1978), which resulted in satisfactory fits. The split lines occur near the center of IC 1318B, and the remaining regions (nonsplit) give lower values of the FWHM (46.9 ± 13.7 km s^{-1}) than for the mean of all regions in IC 1318 (52.2 ± 6.7 km s^{-1}). The region above 41° has an even lower mean FWHM (32.5 ± 12.4 km s^{-1}) than other parts of the nebula. Therefore, in IC 1318B/C we see a much more complex velocity structure along the lines of sight through the nebulae than found in the other objects studied. There is a continuum of velocity values in IC 1318C which defies resolution into individual components. The central parts of IC 1318B are clearly split into two components, but the outer parts of IC 1318B are unresolved and have larger FWHM values than most other nebulae.

III. RELEVANT THEORY

There are several families of theory that may be relevant to interpretation of the large-scale mass motions observed in these three regions. There are the classical expansion, the ionization breakout, the stellar wind, and the supernova impulse models. Each has been thoroughly

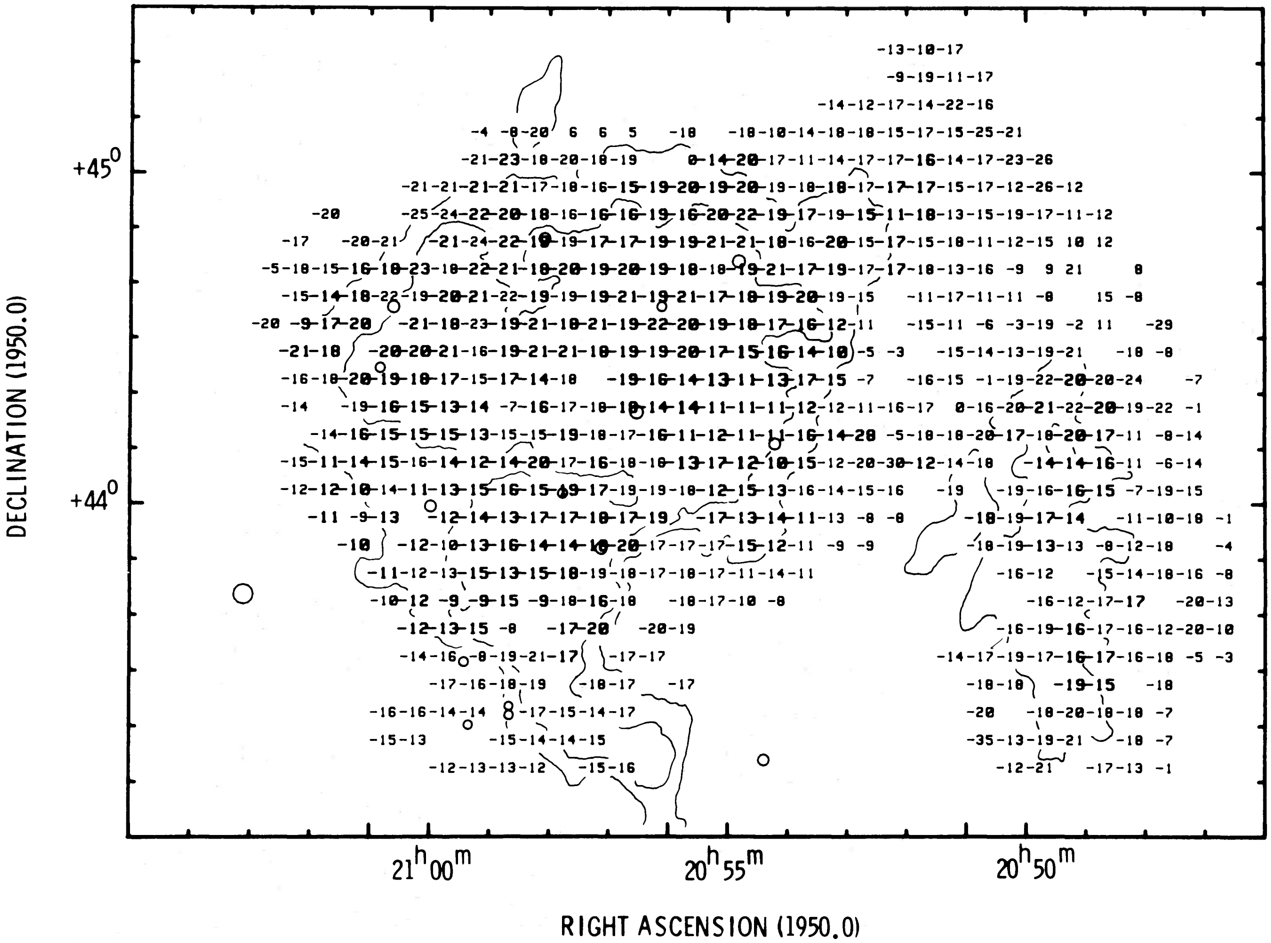

FIG. 3.—The same as Fig. 1 (heliocentric velocities) except for the North American Nebula complex (NGC 7000 and IC 5070)

described in the literature and will only be given a brief summary here.

The classical model (Spitzer 1968) derives from consideration of the large pressure change that should be created upon ionization of a neutral cloud by a bright, centrally located early spectral type star. The advancing ionization front and compressive shock will, in general, produce subsonic expansion of the entire ionized region together with a thin, compressed neutral outer shell. Since the sonic velocity is about 10 km s^{-1} and observed velocities are often much higher, other models are obviously necessary.

The ionization breakout models are a straightforward extension of the above gas dynamical models into the situation where the ionization front at one point reaches the density boundary of the original gas cloud. In this case the pressure difference at the point of breakout is very large and the ionized gas undergoes a free expansion into the surrounding low density medium. The models of Tenorio-Tagle (1979) and his collaborators have shown that the originally spherical H II region will essentially empty itself through the hole in the density wall, hence the description of this as the champagne phase. The velocities reached near the orifice can be several times the sonic velocity, but this will be restricted to a limited volume and the brief period of emptying of the vessel.

The stellar wind models add the consideration of the effects of a high-temperature, high-velocity gas to the gas dynamical models. The necessity of such models is based on the observational fact that the most luminous ionizing stars also have a significant energy flux in their stellar wind. The low efficiency of conversion of stellar photon energy into gas motion means that the effects of simple gas dynamics and the stellar wind are often comparable. The models summarized by Dyson and Williams (1980) show that the stellar wind can produce a thin shell of dense, ionized gas expanding outward at supersonic velocities. This condition would apply until the compressed shell of H II has reached the ionization boundary. The detailed model has not been carried beyond this point, although it is obvious that expansion must continue, although probably at a lower velocity.

The supernova impulse model (Dyson and Williams 1980; Elmegreen and Lada 1977) considers the late stages of expansion of supernova-ejecta into a dense surrounding medium. In this case there is a well-defined

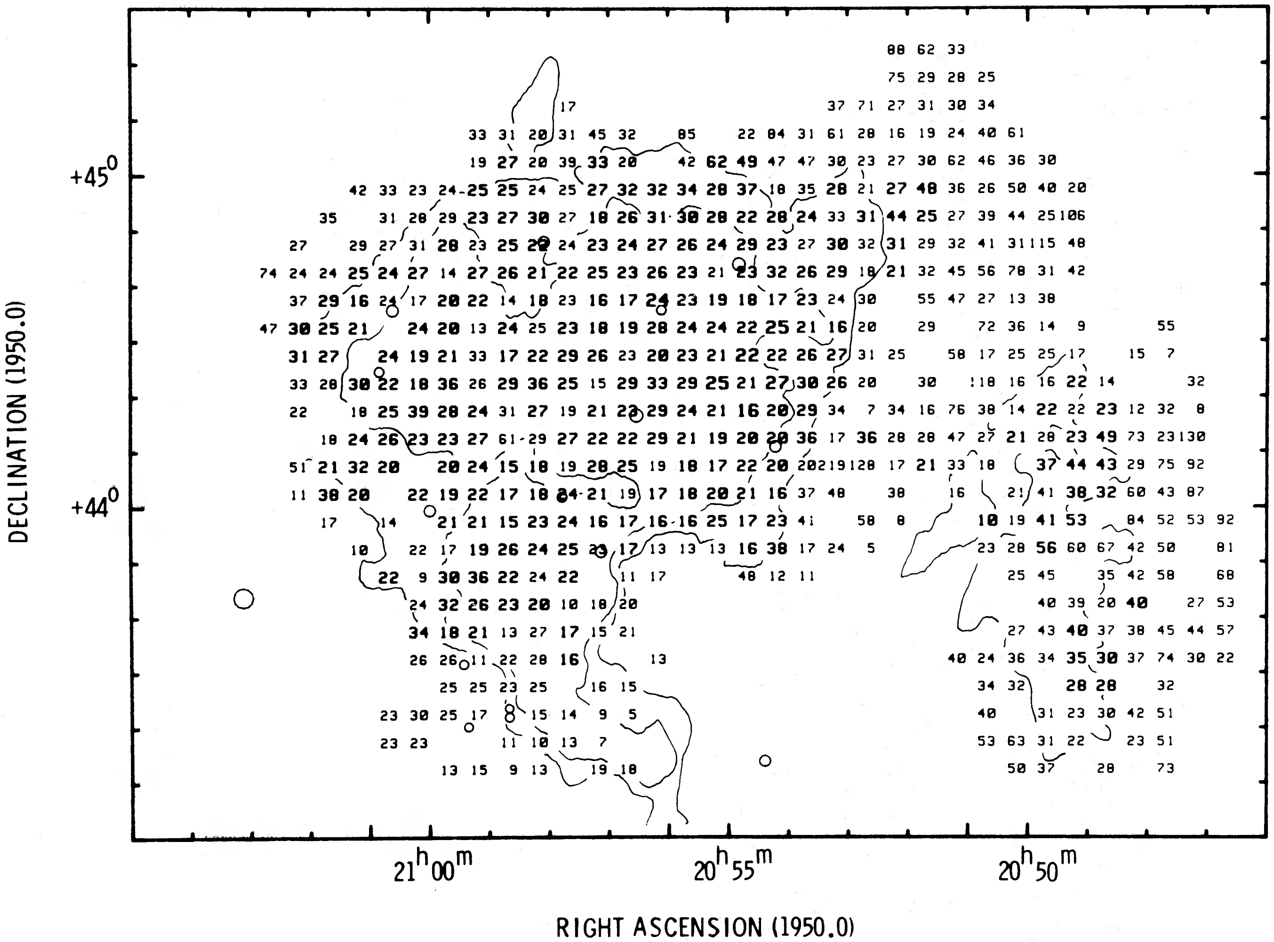

FIG. 4.—The same as Fig. 2 (FWHM) except for the North American Nebula complex (NGC 7000 and IC 5070)

contribution to the kinetic energy of expansion, and this occurs over a brief period. Since this energy is about 10^{51} ergs, the effect on a surrounding cloud can be significant, but will, of course, be present in only that fraction of regions containing supernova remnants.

IV. MODELS FOR THESE NEBULAE

The three regions reported upon in this study are very different from one another. The most useful model for each will be explained in this section. The format for the presentation of each will be the same. We first describe the optical observations, primarily our own. Then we describe the related observations made at other wavelengths, primarily radio. We then summarize the data on the internal velocities and recall relevant aspects of various theories. Finally, we present our model.

a) *NGC 1499*

Unlike the other nebulae studied, NGC 1499 is different in that its ionizing star probably is not generically related. The relative radial velocity is large, and ξ Persei is thought to be a runaway star (Elmegreen and Elmegreen 1978). This nebula shows a nearly constant radial velocity and FWHM distribution across its surface, within the probabilities of the determinations. The agreement of our data with the earlier work argue for their accuracy. Our mean velocity of $+0.5 \pm 4.0$ km s^{-1} for the ionized gas should be compared with the H I emission from near this region at 4–6 km s^{-1} (Sancisi 1970). A more extensive study of CO in the dark cloud L1449 (Lynds 1969) to the northeast of the optical emission was done by Elmegreen and Elmegreen (1978). They found the main CO components to be between -1 and $+6$ km s^{-1}, and an additional component at 8.8 km s^{-1} was also seen.

There is no substantial evidence for mass motions in this cloud. The H I and CO values center about $+3$ km s^{-1} and the optical nebula at 0.5 km s^{-1}. Furthermore, there is no obvious difference in the two halves of the bright central bar when divided into portions closer and farther from the ionization boundary along the northeast edge.

The most relevant theory that applies to NGC 1499 is the simplest considerations of the interaction of an ionization front in a cloud (Tenorio-Tagle 1976). Assuming that NGC 1499 represents an ionization-

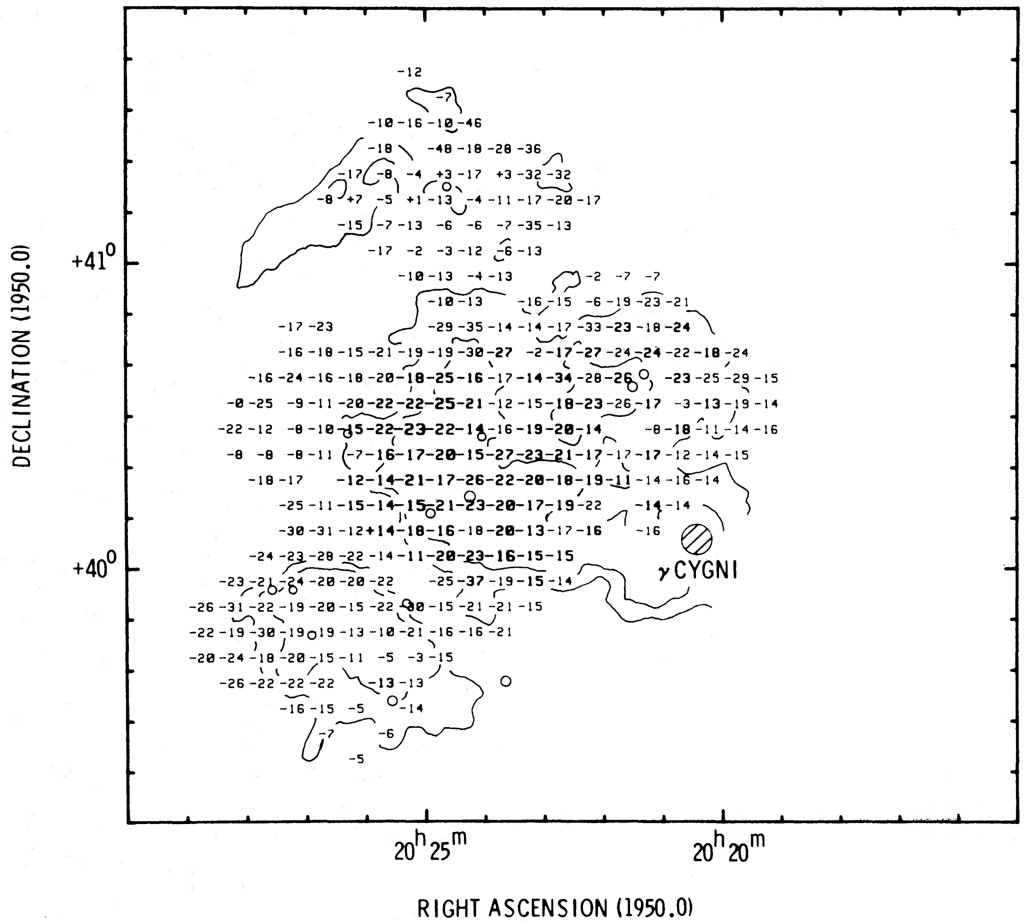

FIG. 5.—The same as Fig. 1 (heliocentric velocities) except for IC 1318B/C

bound nebula caused by a chance encounter of an ionizing star with a cloud that covers only a part of 4π steradians as viewed from the star, the problem reduces to consideration of a plane-parallel geometry. Once the ionization front has progressed to its quasi-equilibrium position, a large pressure gradient will exist between it and the low density region between the cloud and the star. This large pressure gradient would lead to flow velocities away from the front at about 20 km s^{-1}. Assuming a distance of 350 pc (Bohnenstengel and Wendker 1976), the time scale for separation of the star and the nebula would be about 10^5 years. This argues that we are seeing NGC 1499 almost edge-on to the ionization front, and the age could be as much as 10^5 years. An alternative is that we see it at a significant angle to the ionization front, and the absence of a rapid flow of ionized gas away from the front indicates a time scale much shorter than 10^5 years. We prefer the edge-on–view geometry, as the longer time scale model appears to agree with the growth time for the elephant trunk structures that mark the boundary (Elmegreen and Elmegreen 1978).

b) *NGC 7000*

This object is obviously dissimilar to NGC 1499. In this case we have a roughly circular radio continuum (Goudis 1976) centered just off the "Florida Coast" region indicating a spherical gas cloud, with some indication (Carruthers, Heckathorn, and Gull 1980) of an ionization boundary in the southeast portions (at the "Mexican Coast"). The optical appearance is distorted by the dark lane separating the NGC 7000 and the IC 5070 portions of the W80 complex. The exciting star may be HD 199579, which is of spectral type O6, although the adequacy of its ionization luminosity has been questioned (Goudis 1976). If there is another, even more luminous, early-type star, it is probably hidden behind the dust lane. Our radial velocity measurements indicate no systematic variations about the radio continuum center, although there are small but statistically reliable variations across the face of the nebula. The differences in FWHM values that were pointed out in § II are even better defined than the radial velocity differences.

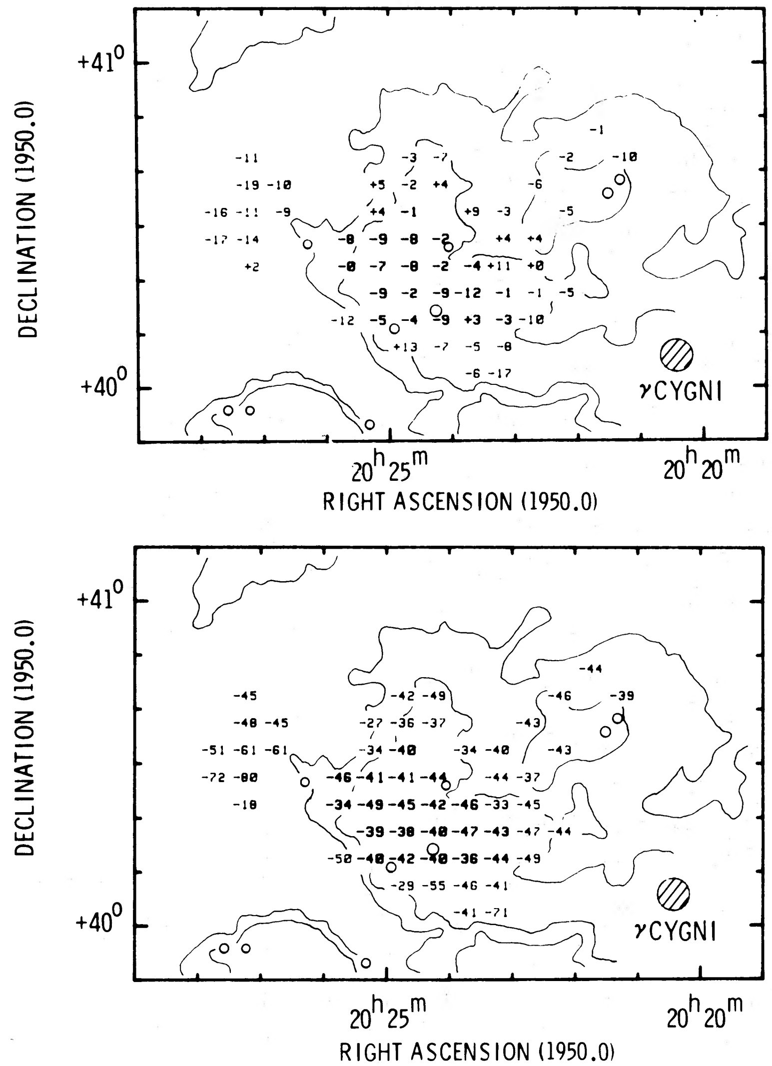

FIG. 6.—The results of the two components of the spectroscopically resolved lines in IC 1318B/C are shown. Fig. 6*a* gives the red component, and Fig. 6*b* the blue.

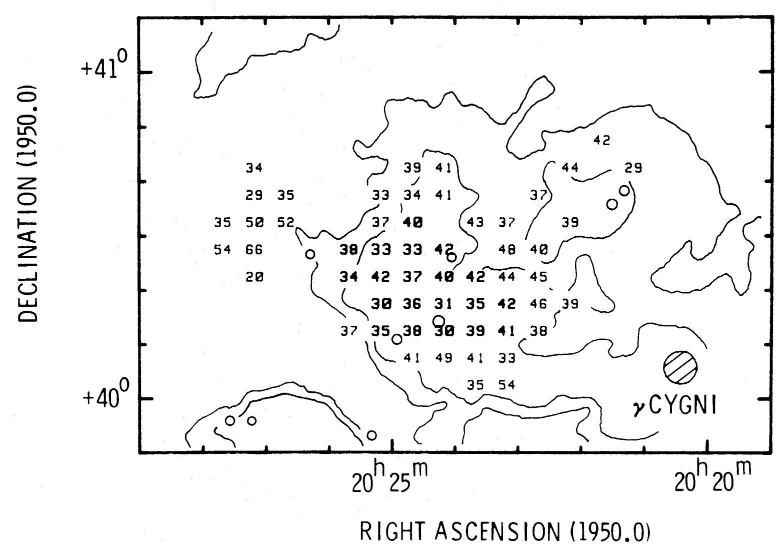

FIG. 7.—The separation (km s^{-1}) of the spectroscopically resolved lines in IC 1318B/C

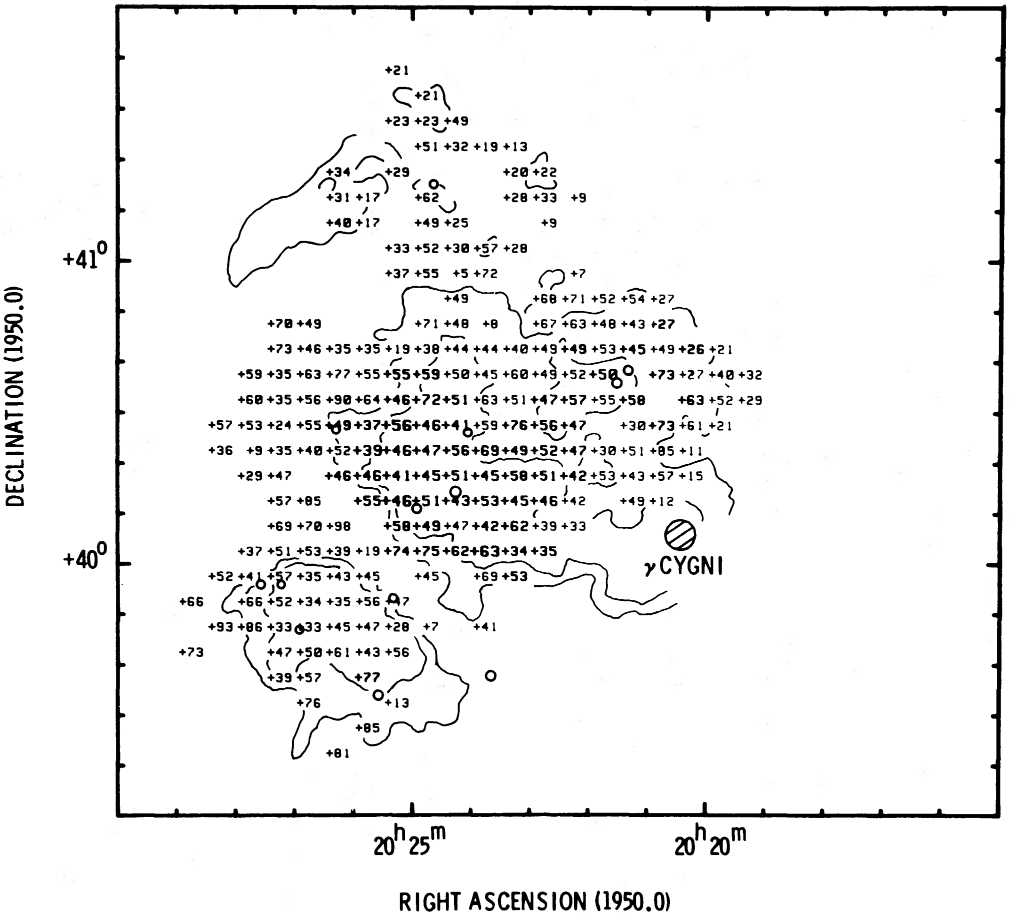

FIG. 8.—The same as Fig. 2 (FWHM) except for IC 1318B/C

The absences of large radial velocity variations and of systematic symmetric changes in FWHM values argue that NGC 7000 is the closest thing we have studied to the classical, gas dynamical ionization bounded spherical nebula. The circular symmetry of the radio emission and the velocity data shown here argue for the inherent simplicity of the region, and the apparent complexity arises from overlying visual extinction (Goudis and White 1979). The very great luminosity required of the ionizing star implies that it should also have a powerful stellar wind. Since the dynamical effects of this wind are not evidenced in the nebulosity, the object must be relatively young. This conclusion is in marked contrast to that of Bally and Scoville (1981) who used their observations of CO line splitting in IC 5070 to argue for a very late evolutionary state of this nebula.

c) *IC 1318B/C*

Due to its proximity to the Cygnus X radio source, this region has been studied by a variety of methods. The far-infrared surveys (Campbell, Hoffman, and Thronson 1980, 1981) show a great similarity to the radio continuum map (Wendker 1970; Baars and Wendker 1974) in showing a continuity of emission along the northwest–southeast line defined by IC 1318B/C, indicating that this is a single emission region with L889 located between the emitting volume and the observer.

The optical results we have derived from our observations are very similar to the [N II] study of Canto *et al.* (1979) but differ markedly from the earlier Hα study by Hippelein (1973). We will assume the validity of our Hα data and of the [N II] study in modeling this region. The nonsplit Hα lines in IC 1318B give a heliocentric velocity of -16.7 ± 4.7 km s^{-1} which is similar to that of the IC 1318C lines (-17.9 ± 5.7 km s^{-1}). Both of these closely fit the H_2CO measurements (Dickel, Seacord, and Gottesman 1977) of -15.8 km s^{-1} for the dark lane L889. The CO observations of Cong (1977) show a component in the -17 to -12 km s^{-1} range, indicating that this is part of the same complex at about -16 km s^{-1}. There is a CO component in the -25 to -17 km s^{-1} range perpendicular to L889 and running across IC 1318C. This emission is probably from a part of this complex having slightly different geometery. With these exceptions, the range of $+8.5$ to -41.5 km s^{-1} is free of emission in the immediate vicinity of IC 1318B/C. Therefore, we have evidence of a single complex of ionized and neutral gas, all at a basic velocity of -16 km s^{-1}. The FWHM observations indicated the central parts of IC 1318B to be split into two components at -5.0 ± 3.7 km s^{-1} and -43.2 ± 5.2 km s^{-1}, and the IC 1318C central region has similar velocity components present, but the lines are unresolved, indicating gas is present at the velocities in between.

The model that best explains these observations is shown in Figure 9, where we have shown a cross section through IC 1318B/C. The complex is split into two major components at IC 1318B, one of which is larger since the red component is stronger. The IC 1318C portion has velocities over a large and continuous range, indicating the structure shown. This model should be compared with that of Baar and Wendker (1981) who concluded that IC 1318B/C were separated regions, possibly connected. Their high-resolution hydrogen continuum study is useful and may indicate that the H II region in our model pinches down in the middle.

The remaining question is how the structure can be generated. We believe that the most likely explanation lies with a strong stellar wind acting on the ionized gas. This mechanism dominates the IC 1318B region, where a shell of ionized material is believed to be pushed apart. If this shell is the result of a compressive shock wave advancing into an H II region, then the shell can be overlain by an outer neutral shell which has not yet been reached. The IC 1318C region does not have such an overlying layer of neutral material except for the CO cloud located at the end. In the forward and back areas the H II region has reached the high-density gas limit and is undergoing supersonic expansion into the surrounding low-density regions, analogous to the champagne phase described by Tenorio-Tagle, Yorke, and Bodenheimer (1979).

V. DISCUSSION

Our earlier papers in his series described studies of two very dissimilar regions, the Rosette Nebula (Fountain, Gary, and O'Dell 1979) and NGC 6611 (Mufson *et al.* 1981). The models generated from those studies can be combined with those reported in § IV to produce a more comprehensive picture of the dynamics of H II regions.

The observations of the Rosette Nebula indicated that the nebula as a whole was undergoing a general expansion or contraction at about 20 km s^{-1}. The lines in the central portion were sufficiently separated and the variation in the FWHM values with distance from the center varied in a fashion to indicate a smooth gas motion, peaked in the bright ring. Although the ratio of intensities of the separated velocity components gave marginal evidence of contraction, rather than expansion, the cavitation time scale for filling the central hole was uncomfortably short. We prefer to interpret the data as expansive motion, although the available observations

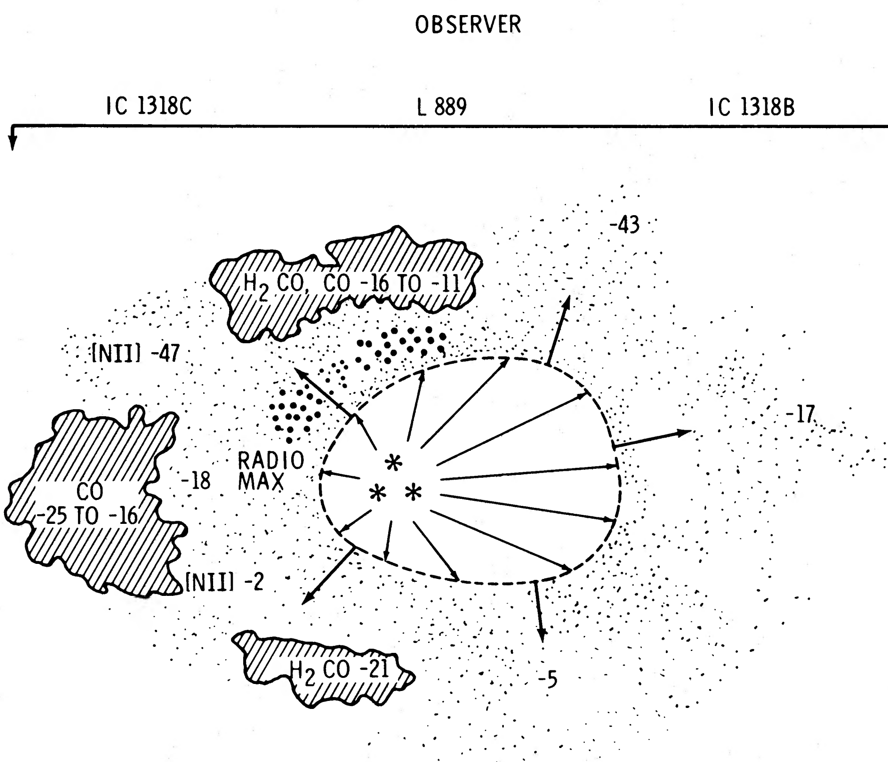

FIG. 9.—A schematic representation of our model for IC 1318B/C, shown cross section perpendicular to the plane of the sky and passing through the middle of IC 1318B/C. The ionizing stars are shown as six-pointed figures and regions of progressive density by heavier depiction.

do not allow discrimination from collapse. The most probable source of energy for the central hole and the general expansion is a strong stellar wind (Smith 1973), which can, to a first order of accuracy, explain both the structure and dynamics of the nebula and possibly even the elephant trunk structures that are so well defined in this object (Schneps, Ho, and Barrett 1980).

The model generated for NGC 6611 from many types of observations was quite different. We envisioned this to be an H II region caused by a young star cluster located at the edge of an extensive neutral cloud. On one side there is an abrupt ionization boundary which holds back the ionized gas motion. On the other sides there are areas that are ionization bounded, some of them marked by elephant trunk structures, and other areas where the gas is directly streaming out at high velocity into the low-density surrounding regions.

When we consider the best models for all five regions we see several important similarities and differences. We will discuss them in what are their natural groupings.

The Rosette Nebula and IC 1318B/C are dynamically similar, although very different in appearance. They both show expansions of about 20 km s^{-1} which are probably driven by stellar winds. The velocities and expansive kinetic energies involved (1.2×10^{49} and 4×10^{49} ergs, respectively) are compatible with the particle flux from stars bright enough to ionize these large regions. The symmetry of the Rosette Nebula means that it is much easier to interpret than IC 1318B/C, where obscuring material makes visualizing the complete nebula much more difficult. Nonetheless, we believe that both regions are fitted by the same model and are dominated by the same mechanism.

The North American Nebula complex is inherently simpler, and the radio continuum appearance leads to a rather simple geometry. The optical observations show the nebula to be ionization bounded, and the radial velocity data give no evidence for large internal velocities. This means that gas dynamics dominates this region, at least at this point of its evolution. The natural question that now arises is, why do we not see the effects of a stellar wind? The easy answer is that there is no stellar wind. This is possible, especially since a stellar outflow has not been established in the best candidate for the ionizing star. If the true ionizing star is actually behind the dark lane, this argument may or may not apply. Another alternative explanation of the absence of the effects of a stellar wind is that the compressive shock has not proceeded far enough to affect large regions of the nebula. The final alternative is that the compressive shock has reached the ionization boundary and lost its momentum to a more massive overlying neutral shell. Since this phase of evolution has not been theoretically modeled, this alternative remains speculative but deserves theoretical study.

The California Nebula and NGC 6611 are dynamically closely related. The major determining factor is the presence of a massive neutral hydrogen wall on one side, defining a limit to gas motion in that direction. Beyond this common feature they differ. The California Nebula's exciting star can only have been in the vicinity for a brief period, and there seems to be no impediment to flow away from the ionization front. NGC 6611 has neutral gas regions on the opposite side of the exciting star cluster. These regions cause smaller, local ionization fronts to be formed and direct the flow of ionized gas out into the low-density surrounding region.

This summary has shown that the development of observational techniques for spatial velocity mapping of diffuse nebulae verifies the need for the recently derived theoretical models. The theoretician's model is usually not seen, but we are able to show that some nebulae do agree with models using stellar winds and massive ionization boundaries. In both cases the effects on the time scale of evolution are significant. In the case of the stellar wind dominating an evolving nebula, the particle flux from the exciting stars can considerably add to the kinetic energy of expansion and the formation of high density outer shells.

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W. F. FOUNTAIN and G. A. GARY: ES62, Marshall Space Flight Center, AL 35812

C. R. O'DELL: Department of Space Physics and Astronomy, Rice University, P.O. Box 1892, Houston, Tx 77251