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INTERNAL MOTIONS IN H II REGIONS. XII S162 AND NGC 7635

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RESUMEN

Se discute la estructura aparente de S162, así como de la Nebulosa de Burbuja (NGC 7635) asociada a ésta, usando fotografías directas tomadas con filtros de interferencia de banda angosta (10 Å) en la líneas de Hα, [N II] λ6584 y en el continuo en λ6607 Å. Los resultados de este material se discuten junto con el campo de velocidades en S162 en especial de la Nebulosa de Burbuja en unos 300 puntos obtenidos por interferometría Fabry-Pérot fotográfica. Se muestra que "la burbuja" está compuesta de discretos amorfos y muy regulares arcos; todos ellos descritos sobre una capa esférica gaseosa en expansión de 4 km s^{-1}. Los arcos están probablemente relacionados genéticamente con los glóbulos que constituyen la formación "cometaria" dentro de la Burbuja. La fuente de ionización de S162 es la estrella BD + 60°2522 de tipo O7I_bf clasificada con nuestros espectros de alta resolución. Tentativamente sugerimos que el glóbulo más brillante puede ser un brote de la estrella, que este globulo ha generado el siguiente glóbulo y éste a su vez ha generado el tercero. La configuración de NGC 7635 sugiere que campos magnéticos son operantes en la región. Polarimetría en la región óptica y de radio así como estudios de alta resolución tanto en el infrarrojo como en velocidades son deseables para proponer un modelo satisfactorio para esta nebulosa.

ABSTRACT

The apparent structure of S162 and of the Bubble Nebula (NGC 7635) associated with it, is discussed using a number of direct images taken through narrow band (10 Å) interference filters in Hα, [N II] and in the continuum at λ6607. The results are discussed together with the radial velocity field of S162 and in particular of the Bubble Nebula as obtained from photographic Fabry-Pérot interferometry. The Bubble Nebula is shown to be composed of distinct and amorphous very regularly curving arcs, all inscribed on a tenuous slightly ellipsoidal shell of gas expanding at velocity of about 4 km s^{-1}. The arcs are probably genetically related to the globules which form the characteristic comet-like feature within the Bubble Nebula. The ionization source of S162 is BD + 60°2522 and O7I_bf star classified from our high dispersion spectrum. Our very tentative suggestion is that the brightest globule may be an offshoot of this star and that the globule has generated the next globule which in turn may have generated the third one. The configuration of NGC 7635 suggests that magnetic fields are likely to be operative in the region. Polarimetry in the optical and in the radio range as well as high resolution infrared studies, high resolution velocity fields are desirable to find a satisfactory model for this nebula.

Key words: **EMISSION NEBULAE – H II REGIONS, FABRY PEROT VELOCITIES – GLOBULES-INFRARED.**

I. INTRODUCTION

The emission nebula Sharpless 162 –with representative coordinates l = 112.2, b = + 0.2– has dimensions roughly of 40 × 40 arcmin. The brightness distribution is characterized by a great deal of detail, the most striking ing one being NGC 7635 the so-called Bubble Nebula with a comet-like feature within its boundaries. The different parts of S162 appear to be embedded in a weak emission background. This nebula together with S157 and S158 falls within a local maximum of hydrogen distribution which suggests that all three are associated with the same H I complex (Israel 1977).

A considerable number of investigations have been reported to-date particularly dealing with NGC 7635. Johnson (1971) had suspected that the latter object might be a planetary nebula projected by chance on the region. This is ruled out at present as the optical radial velocities determined since then in NGC 7635 and S162 are comparable (Maucherat and Vuillemin 1973).

Fluxes at 10 different radio frequencies in the range 750 to 85000 MHz are obtained by different authors. A complete listing of these is given by Israel, Habing, and De Jong (1973). In that paper the latter authors present and discuss their detailed aperture synthesis map of the continuum radiation at 21-cm. The radio features they obtain show good agreement with the optical ones. In a subsequent paper Israel has given isophotal contours in the λ6 cm beam continuum where the "comet tail" structure is clearly distinguishable (Israel 1977).

It is generally agreed that the ionization source of

S162 (and of NGC 7635) is BD+ 60°2522, an Of star, which is located off-center in the Bubble Nebula, a circumstance which is rather intriguing. Deharveng (1973) has presented spectrographic observations of NGC 7635 at two different positions along the comet feature. The conclusion drawn is that the feature is clumpy, and that its electron density is very high.

A radial velocity field from the Hα line at 62 points in and around the Bubble Nebula is given by Maucherat and Vuillemin (1973) with a marginal indication that the shell is expanding (or contracting).

In this paper we give a discussion of the morphology of the region and present the detailed velocity field of S162 including NGC 7635. Furthermore, we discuss our results in connection with previously published work on different aspects of the nebula.

II. OVERALL MORPHOLOGY OF S162

Figure 1 (Plate) is an enlargement of an image tube photograph of the brightest part of the nebula through a 10 Å half-width interference filter at [N II] λ6584 Å, taken with a focal reducer mounted at the Cassegrain focus of the 1-meter reflector at the Tonantzintla Observatory. Note that there is a larger ring in S162, more tenuous, wider, and less well marked than NGC 7635. That ring appears to cross the crescent formation, the ionizing star BD+ 60°2522, and also seems to go through the brightest star in the field to the southwest BD + 60°2521 (B5 IV). The association of the bright star with S162 is fortuitous for it is a foreground object at a distance not exceeding 0.5 kpc whereas S162 is at a minimum distance of around 3 kpc.

The rather long exposure brings out the fainter parts of the nebular complex S162 but conceals the details of the crescent shape of NGC 7635 at the northern edge of the Bubble Nebulae and the comet-like structure, particularly in reproducing it in print. The ionizing source, the star BD + 60°2522,is indicated in that figure. In the northern part of S162, bright dense globules and comet-like features are singled out by previous workers (see for example Barlow, Cohen, and Gull 1976).

For the sake of completeness we reproduce in Figure 2 (Plate) a wider field, long-exposure interference filter image in Hα where a larger portion of the overall S162 is exhibited, taken with a focal reducer and the 83-cm reflector at the Observatory in San Pedro Mártir.

Inspection of the original film of Figure 1 suggested to us that the crescent configuration of NGC 7635 proper might show fine structure. For a study of the crescent and the come-tlike structure more closely, we took a series of short exposures in Hα and [N II] λ6584 Å lines with the same equipment at the 2.1-m reflector mentioned above. We shall discuss the yield of these data later in this paper.

III. THE OBSERVATIONS OF S162 PROPER

We have performed Fabry-Pérot interferometry covering the brightest central area of S162. A focal reducer was used in conjunction with the 2.1 m reflector of the Observatory at San Pedro Mártir and the 1 m reflector at the Observatory in Tonantzintla. The interference filters used are all of 10 Å halfwidth at the mean λ as specified in the observation log. The étalon employed has a free spectral range of 283 km s^{-1} and a finesse of 10. The interferograms were measured with a Mann comparator of the Johnson Space Center of the NASA and on photographic enlargements. The reductions are performed following the scheme advanced by Courtès (1960). Information relevant to three interferograms used for the general velocity field is presented in Table 1. The data are arranged as follows: column 1 is the plate number; the second and third columns give the coordinates (1980) of the plate center; the fourth column specifies the telescope used; the fifth the interference filter for each interferogram; the sixth, the mean velocity, rms deviation, and the number of measured points; the seventh the exposure time, and the last column gives the date of the observation.

The average velocities from the three interferograms covering a large portion of S162 are comparable indicating that no systematic effects exist between the results from the different interferograms. The velocity data can therefore be combined for a discussion of the overall field. The average velocity from the three interferograms is -51 ± 3.5 km s^{-1} from all 267 points, and this is adopted as the systemic velocity of S162.

We now compare our average velocity of S162 with earlier determinations from both optical and radio regions. Table 2 lists the data, all referred to the LSR. Except for two cases there is fair agreement between the V_{LSR}'s; in the first case we believe that there is an error in the caption to Figures 1 and 2 of Maucherat and Vuil-

TABLE 1

INTERFEROMETRIC DATA ON S162

Interferogram	Coordinates (1980) α	Coordinates (1980) δ	Telescope	Filter	V_{hel} (km s^{-1})	Exp Time (min)	Date of Observation
FI 856	$23^h19^m57^s$	+61°4′. 2	2.1 m	[N II] λ6584	− 51.41 ± 5.06 (134)	20	30 Oct. 81
FI 867	23 19 45	+61 8 .51	1 m	[N II] λ6584	− 49.36 ± 5.24 (40)	25	27 Nov. 81
FI 868	23 19 40	+61 7 .53	1 m	[N II] λ6584	− 51.31 ± 4.02 (93)	35	27 Nov. 81

TABLE 2

VLSR OF S162 BY DIFFERENT METHODS AND AUTHORS

Feature	Method	V_{LSR} (km s^{-1})
Hα	interferometry	– 46 (1); – 45.2(2); – 54 (3)
[N II] λ6584	interferometry	– 42 (4)
Several λ's	spectral	– 46 (5)
H 109α	radio	– 44.1 (6)
H 137β	radio	– 41.2 (6)
H 21 cm	radio	– 52 (6)
CO	radio	– 44.7 (7)

1) Deharveng 1973; 2) Georgelin 1975; 3) Maucherat and Vuillemin 1973; 4) this paper; 5) Miller 1968; 6) Kazès *et al.* 1977; 7) Blitz *et al.* 1982; the first dection of CO in S162.

lemin's paper in the sense that the velocities are heliocentric and not referred to the LSR. Thus their V_{SLR} should probably read –45 km s^{-1}. The second case concerns the H I velocity which is more negative by about 8 km s^{-1} (Kasès, Walmsley, and Churchwell 1977) with respect to the average of the rest (– 44 km s^{-1}). A discrepancy in the same sense between optical emission-line velocities and that from H I by Kazès *et al.* (1977) was noted earlier in the case of S152 (Pişmiş and Hasse 1980). It is not clear from the available data whether the discrepancy is due to a physical cause or to a systematic error in the H I velocities.

IV. THE GENERAL VELOCITY FIELD

We have deemed it unnecessary to display the individual velocity points of the three interferograms listed in Table 1. Rather we divided the region into subregions following the morphological details of the emission nebula (such a subdivision may be quite subjective). Figure 3 gives the subregions and the average radial heliocentric velocities in each one with standard deviation and the number of points. There do not seem to be large variations between the average velocities. We note however that the wing at the eastern edge of the Bubble Nebula is approaching while its center is receding with respect to S162 as a whole. The LSR systemic motion is –41.3 adopting a V_{SSM} of 9.7 km s^{-1}. Based on the Schmidt model the kinematic distance of S162 with this V_{LSR} velocity would be 3.37 kpc in agreement with earlier determination (Israel *et al.* 1973). We note that the periphery of the Bubble Nebula has the same velocity as the systemic velocity of S162. As regards the high excitation region in the north (north of NGC 7635) the velocities are gradually blueshifted towards the east and the east-west difference is around 6 km s^{-1}. We note also that the center of the Bubble Nebula is by 3.6 km s^{-1} redshifted. If this denotes an expansion of the Bubble, the isotropic expansion velocity will be around 4 km s^{-1}. With this velocity the Bubble will have reached its present extent in $\simeq 3.6 \times 10^5$ years (the expansion age).

V. THE STRUCTURE OF NGC 7635

A series of short exposure interference filter direct photographs in different spectral regions centered on the Bubble Nebula were secured with a focal reducer attached to the 2.1 m reflector at the Observatory in San Pedro Mártir with the aim of bringing out the structural details of the "Bubble Nebula". Four such photographs are shown in Figures 4 to 7 (Plates). Table 3 lists the data and the figure corresponding to each plate.

The following points can be made from the intercomparison of these figures.

a) The northern section of S162 is of higher excitation than NGC 7635 since it appears much brighter in [N II] λ6584 Å relative to the Bubble (Figure 7) whereas in Hα the reverse is true (Figure 4). The comet-structure is so intense in both figures that no comparison of the kind can be made for that structure.

b) The comet-structure shows three different condensations, the one at the eastern end being the brightest. From it an appendage curls northward (see Figure 5).

c) The fine structure of the "crescent" is as suspected by us, indeed composed of amorphous, very regularly curling arcs. We distinguish three of these arcs. The midle one is a continuation of the appendage of globule A, (to use Israel's nomenclature for the brightest knot in the comet structure marked in Figure 5). To the west of it is another arc which seems to join the third globule at the western edge of the "comet" feature. This arc branches off before reaching that globule, the outer one stretching farther south past the globule. It may be that the outer branch belongs to the larger ring mentioned earlier.

d) There is still another arc which at cursory inspection seems to join the Of star and continues to end at globule A_1. Since the other two arcs show definite association to the globules we strongly believe that the coincidence with the star is fortuitous and that the arc is genetically related to globule A_1.

e) Although all arcs are comparable in brightness in

TABLE 3

IMAGING DATA ON NGC 7635

Plate	Filter	Exposure Time	Ref. Figure
FI 894	Hα, λ6563	1 min	4
FI 898	[N II] λ6584	1 min	5
FI 928	Cont. λ6607	60 min	6
FI 934	[N II] λ6584	5 min	7

Telescope: 2.1-meter

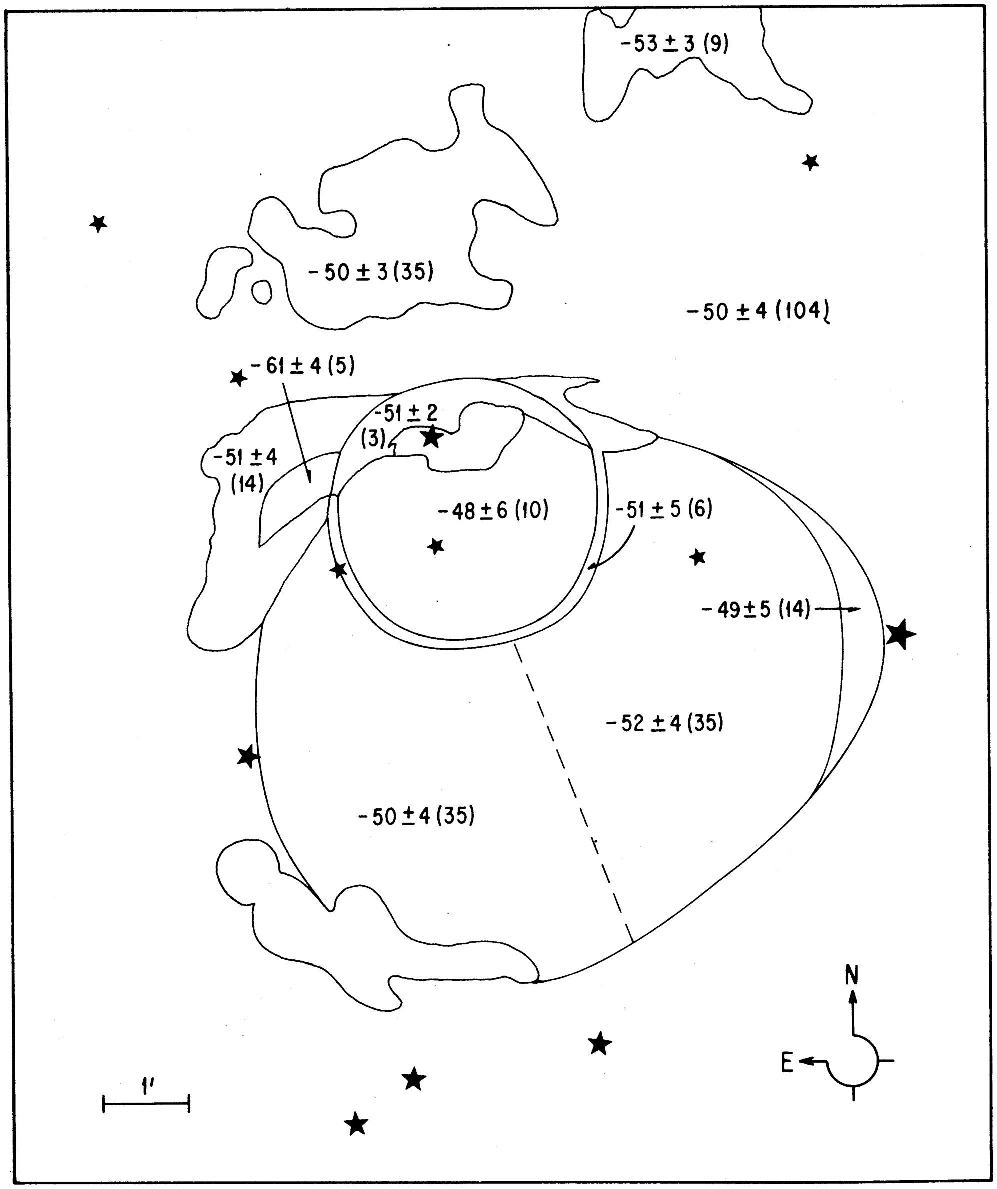

Fig. 3. The scheme of the subdivisions of S162. Within each subregion the average radial heliocentric velocity is inscribed together with its r.m.s. errors and the number of points.

the [N II] line, in the Hα photograph (Figure 4) the middle one, which is the continuation of the appendage of A_1, is much brighter in comparison with the others. This may indicate a difference in the excitation degree of the different arcs.

It is astonishing that the combination of the different arcs (filaments) would delineate such a perfectly circular outline at the brightest northern edge of the "crescent". We suggest, that the filaments are inscribed on an almost spherical tenuous shell of gas.

f) Although the good definition of the details in the comet structure is lost in the reproduction, a faint appendage can be seen symmetrical with the northward curling appendage of globule A_1 (Figure 5).

The 21-cm continuum isophotes by Israel *et al.* (1973) delineate the "crescent" of NGC 7635 while the 6-cm continuum map of Israel (1977) singles out the chain of globules in the comet-configuration in particular the brightest A_1 globule.

VI. VELOCITIES WITHIN NGC 7635

To study in detail the kinematics of the system of arcs mentioned above and of the comet-structure in NGC 7635 we took a series of short exposure interfero-

TABLE 4

INTERFEROMETRIC OBSERVATIONS ON NGC 7635

Interferogram Designation	Coordinates (1950) α	δ	Exposure Time	Filter
FI 916	$23^h20^m43^s$	+ 61 05.0	2 min	Hα λ6563
FI 917	23 20 43	+ 61 05.0	4 min	[N II] λ6584
FI 922	23 20 45	+ 61 05.0	3 min	Hα λ6563
FI 923	23 20 45	+ 61 05.0	5 min	[N II] λ6584

All interferograms were taken on September 19, 1982.

grams in Hα and [N II] λ6584 with centers slightly and gradually displaced in right ascension to ensure a satisfactory coverage and to avoid convolution problems. Only interferograms of the highest quality were measured; these are listed in Table 4.

Figure 8 (Plate) is a photograph of NGC 7635 with average velocities from the four interferograms inscribed on it. The velocities show a tendency to be more positive in the globules. The velocity in the arcs tends towards the systemic value as the arcs approach the outer boundary of the "crescent". We do not attempt to extract more information than that which potographic F.P. velocities can safely yield. We may state however that the comet-like assembly of the globules appears to be located on the far side of an expanding shell (if the shell were contracting they would be on the near side). The arcs are indeed related to the condensations; the fact that these arcs stop abruptly at the comet-like feature and do not continue southward suggests that the filaments most probably have their origin at the globules. It is worth mentioning an attempt by Icke (1973) to account for the regular morphology of the Bubble Nebula as a result of an explosive mass loss from the Of star within the Bubble. According to Icke the shock front produced by the collision of the expanding gas clouds with the surrounding matter with inhomogeneous density can explain the structure of the Bubble. It is not clear whether more detailed morphology in the form of filaments associated with the globules in the comet-structure will be compatible with Icke's model. The almost perfect curvature of the filaments may require a funneling agent such as a magnetic field to be operative. A more detailed determination of the velocity field using a scanning Fabry-Pérot interferometer and polarization measurements, in the optical or in the radio range, of the globules and of the filaments would help shed light on the origin and maintenance of these curious formations.

VII. DISCUSSION OF THE EXISTING PHOTOMETRY AND SPECTRO-PHOTOMETRY OF NGC 7635/BD + 60°2522

As mentioned earlier BD+ 60°2522 is the only known star in S162 that is able to ionize the whole nebula. A detailed classification by Conti and Alschuler (1971) assigns to it a spectral class of O6.5 IIIf; such a star is expected to shed mass at present as many Of stars are known to do. The star is a spectroscopic binary judging from the large variation of its radial velocity (Wilson and Joy 1952) but no orbit is determined as yet.

We have obtained high dispersion spectra of BD+ 60°2522 (V = 8.7) and also of BD + 60°2521 (V =6.9) with a Cassegrain spectrograph attached to the 2.1-meter reflector of the Observatory at San Pedro Mártir, and using a multichannel detector (OMA). The spectral class estimated from the tracings of the ionizing star is O7 I_bf (as against O6.5 IIIf from earlier determinations) while that of BD + 60°2521 is estimated as B5 IV (Bisiacchi (1982).

The spectrum of the Of star will be discussed in a later communication when more data become available. It is interesting to note that the Of star showed the λ4430 interstellar band quite clearly. The spectrum of star BD + 60°2521 also showed a measurable λ4430 band although rather shallow. The ratio of the equivalent width of the band in the Of star to that of the B star yielded about 10, confirming thus that the B star is a foreground object.

We have obtained a direct image-tube photograph of NGC 7635 with exposure of 60 min through a 10 Å halfwidth interference filter centered at λ6607 (a filter used for galaxies redshifted by about 2000 km s^{-1}). That photograph, reproduced in Figure 6, shows a nebulous detail, a continuum south of the bright star BD + 60°2522 and apparently connected with it[1]. The feature, however faint, is definitely coincident with the brightest globule A_1 of the comet-like object. Although we lack quantitative photometry inspection of the figure leads us to the following rather speculative suggestions:

1) There is a genetic relationship between the Of star and globule A_1 and this supports our suggestion that globule A_1 is an offshoot from the Of star.

2) The expulsion of matter from the Of star has been directional and not isotropic. Its stellar wind therefore may also be directional and not isotropic.

1. With the same equipment and with exposure of 60 min we have also detected a continuum in the bright compact H II region S152 (unpublished) a region with very high density of dust (Pişmiş and Hasse 1980).

3) Globule A_1 shows infrared radiation although this may be very weak.

Barlow *et al.* (1976)'s infrared flux measurements of A_1 at 10μ and 18μ have yielded only upper limits of 0.9 and 25 Jy respectively, in line with point (3). On that basis Barlow *et al.* conclude that knot A_1 –and presumably also the fainter knots of the "comet"– are ionized from an external source quite likely by the Of star. However in view of the extended nature of the continuum radiation detected at λ6607 we suspect that the beam used in the infrared observation of Barlow *et al.* (11 arc sec) may include a good portion of A_1 when directed towards the star and in turn a beam centered on A_1 would include part of the star's radiation. Better spatial resolution in the infrared is needed to distinguish between the fluxes of the star and the neighboring globule and to pinpoint the IR source (or sources) and/or to map the continuum.

Infrared luminosities of NGC 7635/BD + 60°2522 are derived by Cohen and Barlow (1973) They list their magnitudes together with earlier determinations, spanning from the ultraviolet to 20μ, both earth-based and from rockets. The rocket observations cover a larger area such that the corresponding luminosities are the averages over S162. Carrying out the necessary normalization the flux versus λ for NGC 7635 shows a thermal spectrum between 0.3μ to 0.6μ (see Figure 1 of the cited paper); it then rises with a positive gradient to 20μ, the last observed point. The conclusion of Cohen and Barlow is that one is seeing thermal re-radiation by dust grains formed in the mass overflow from the Of star and argue against the pre-existence of dust in the vicinity of the hot star since "sputtering by energetic particles would rapidly destroy such dust". This statement may still be open to question; in this respect infrared observations with better spatial resolution and sensitivities of the globules are desirable.

Barlow *et al.* (1976) report on the extinction over S162 and of its ionizing star on the basis of spectrophotometry.Combining their results with radio data they find the extinction to be uniform except at three small regions (C_1, C_2, C_3) in the northern part of the nebula (we do not discuss that region of S162 in this paper), and at A_1 of the comet-structure. The value of Barlow *et al.* (1976) for the extinction of the Of star is 2.26 magnitudes while that for A_1 is 3.34 magnitudes. Accordingly the internal extinction of A_1 is 1.08 magnitudes. Assuming that the depth is comparable to the projected diameter, $\simeq 0.2$ pc (for a distance of ≈ 3 kpc), extinction within A_1 would be of the order of 5 magnitudes per parsec. The density of dust in A_1 is therefore quite high; so far no stars are detected within the globules.

VIII. CONCLUSIONS

A number of direct photographs and Fabry-Pérot interferograms have constituted the basis of the present study on S162. We have not detected large relative motions within the nebula. However, the detailed velocity field and the narrow band interference filter images of the Bubble Nebula within S162 suggest that amorphous filaments (arcs), which together fashion the northern boundary of this circular nebula, are inscribed on a slowly (4 km s^{-1}) expanding tenuous shell. The filaments appear to be genetically related to the chain of three globules which together simulate a "comet". We suggest that the brightest globule closest to the ionizing star of NGC 7635 (and of the whole of S162) is an offshoot from that star and that this globule in turn has given rise to the other globules of the comet-feature. Though S162 is believed to be an evolved region (Israel 1973, 1977) the age of the Bubble Nebula within it is around $3\text{-}4 \times 10^5$ years, and younger still may be the globules and arcs we have described above. These circumstances indicate that although the larger H II region as a whole may be an evolved nebula it includes younger regions. In other words, the constituents of S162 are not coeval, providing thus another case of sequential formation of objects in a cloud. (Pişmiş and Hasse 1976; Recillas-Cruz and Pişmiş 1979). We believe that magnetic fields may be operative in and around the "comet" structure. To venture a definite model for the region in particular of the Bubble Nebula with the existing information, is rather premature. Higher resolution velocity fields, higher resolution infrared work as well as polarimetry of NGC 7635 is desirable especially of the globules and the associated amorphous arcs.

After the completion of the present contribution, Vol. **201** of the *M.N.R.A.S.* was received in which Thronson *et al.* (1982) presented their infrared and radio molecular observations of the Bubble Nebula; they found the emission from CO to be weak, a result already expected from Blitz's earlier results (Blitz, Fich, and Stark 1982). We note that their infrared emission both in 50μ and 100μ shows a maximum in the region where the globule A_1 and its appendage are located.

Our treatment of the Bubble Nebula is in no way altered by the contents of the mentioned paper. We renew emphasis on the necessity of high resolution infrared studies in the detailed features, such as the globules and the filaments in NGC 7635.

We extend our thanks to E. Gastélum for the careful photographic work needed for the measurements of some interferograms and for the reproductions shown in this paper as well as in all earlier papers of this series. We are grateful to G. F. Bisiacchi for obtaining the spectrograms used in this report and for the classification of the spectra. One of us (P. P.) acknowledges the facilities offered at the NASA Johnson Space Center where the measurements of most of the interferograms were carried out.

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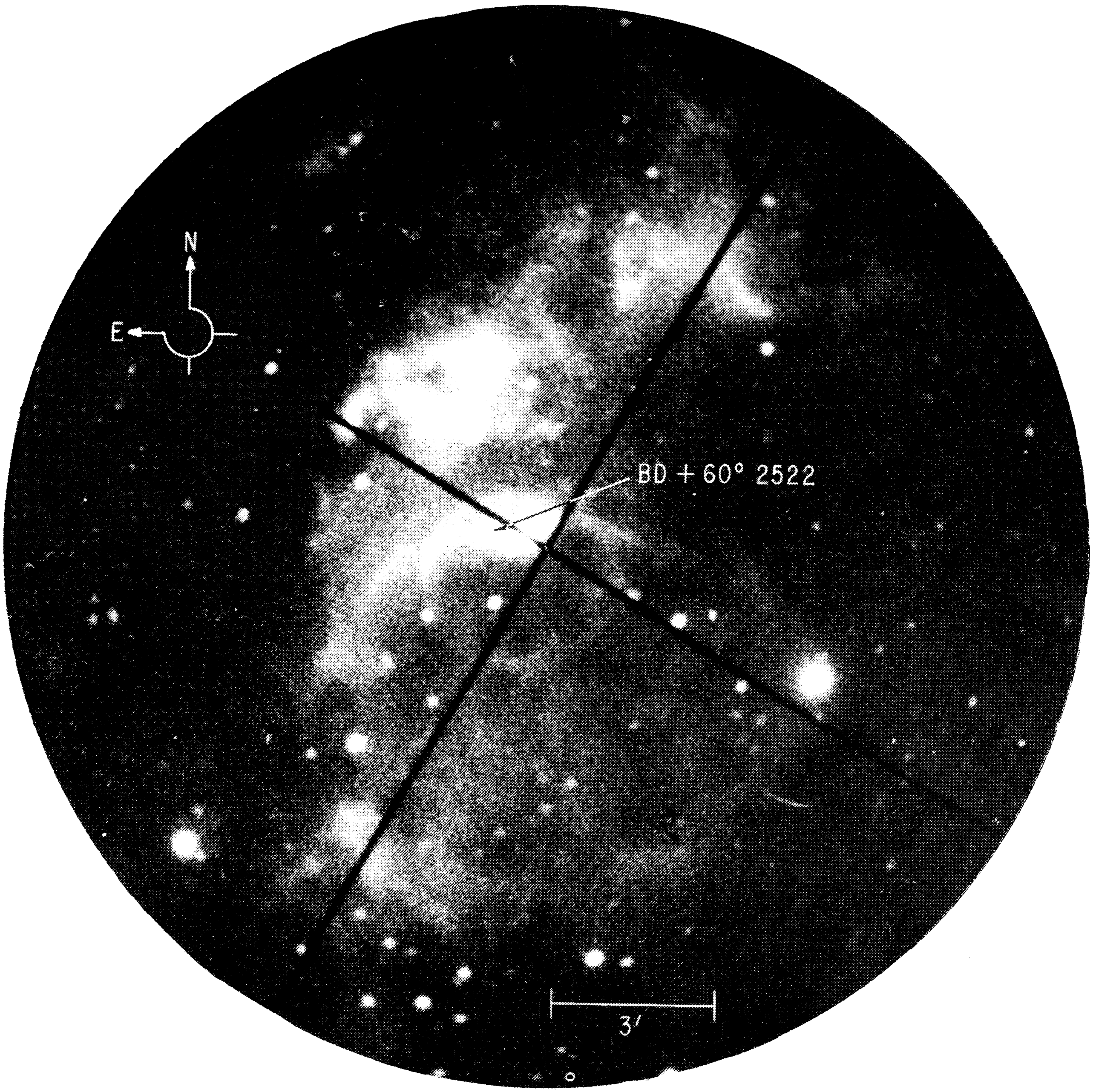

Fig. 1. Enlargement of an image tube photograph of the brightest part of the nebula through a 10Å half-width interference filter at [N II] λ6584Å, taken with a focal reducer mounted at the Cassegrain focus of the 1-meter reflector at the Tonantzintla Observatory.

P. PIŞMIŞ *et al.* (See page 51)

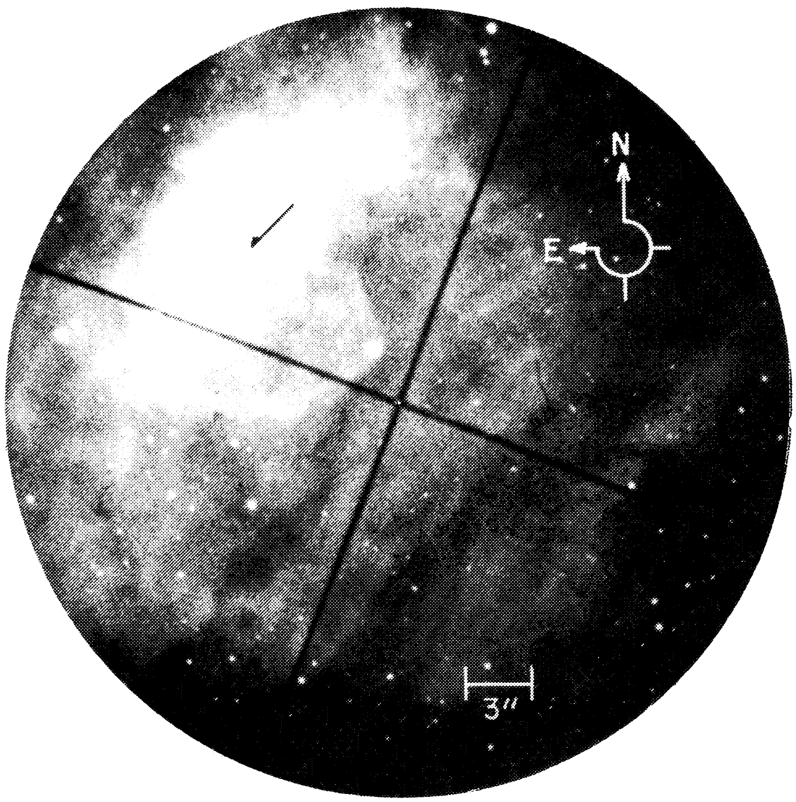

Fig. 2. Enlargement of an image tube interference filter photograph covering a wider field of S162, taken in Hα. A focal reducer was used together with the 83-cm reflector at San Pedro Mártir Observatory. An arrow points to the ionizing star BD + 60°2522. (Exp. time 15 min).

P. PIŞMIŞ *et al.* (See page 51)

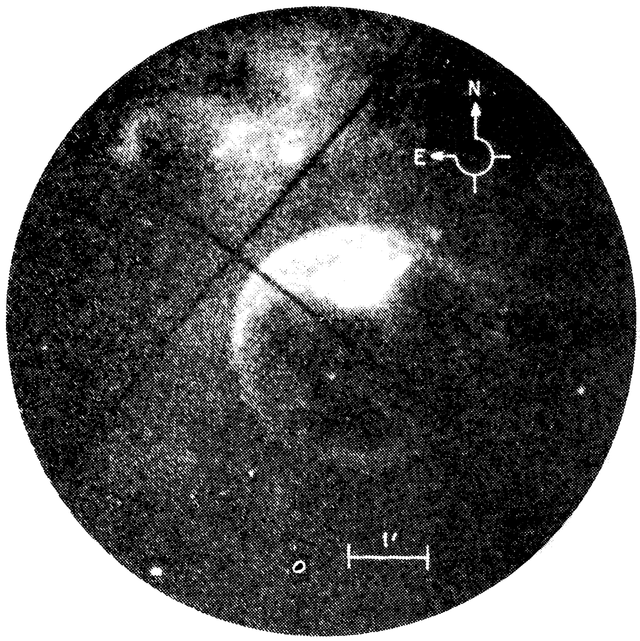

Fig. 4. Filter Hα λ6563

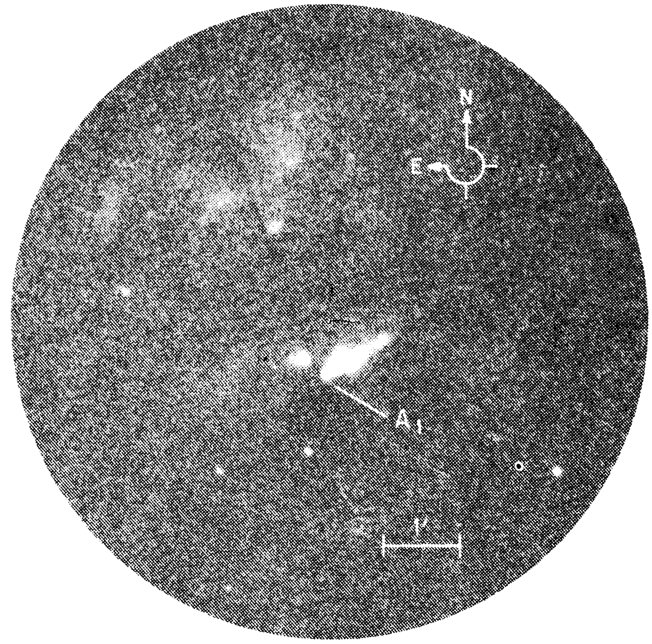

Fig. 5. Filter [N II] λ6584

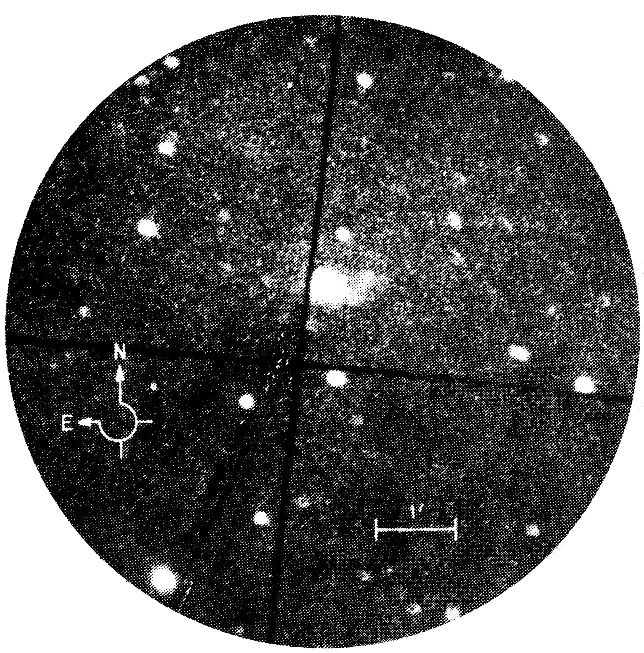

Fig. 6. Filter λ6607 continuum

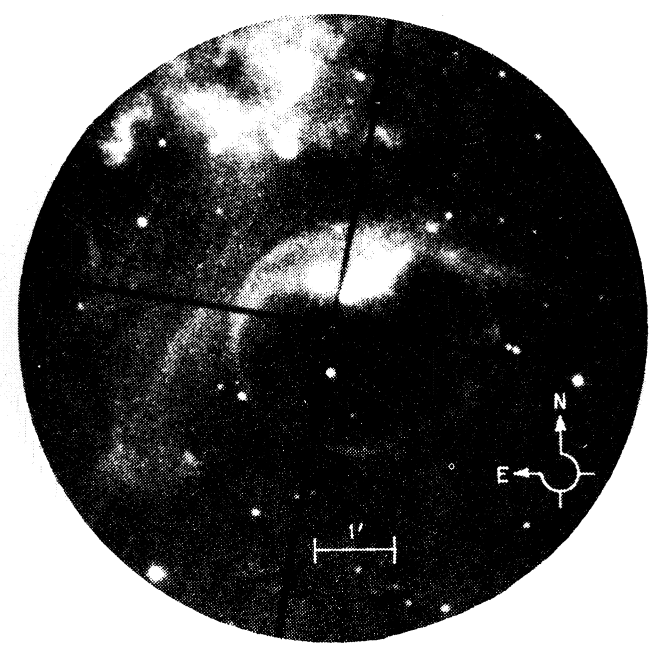

Fig. 7. Filter [N II] λ6584

Figs. 4 to 7. Short exposure interference filter direct images in different spectral regions, centered on the Bubble Nebula, obtained with a focal reducer attached to the 2.1 meter reflector at the Observatory in San Pedro Mártir. Globule A_1 is marked in Figure 5. The full width at half transmission of all the filters is 10Å. The scale on the original film is 48 arcsec mm^{-1}.

P. PIŞMIŞ *et al.* (See page 51)

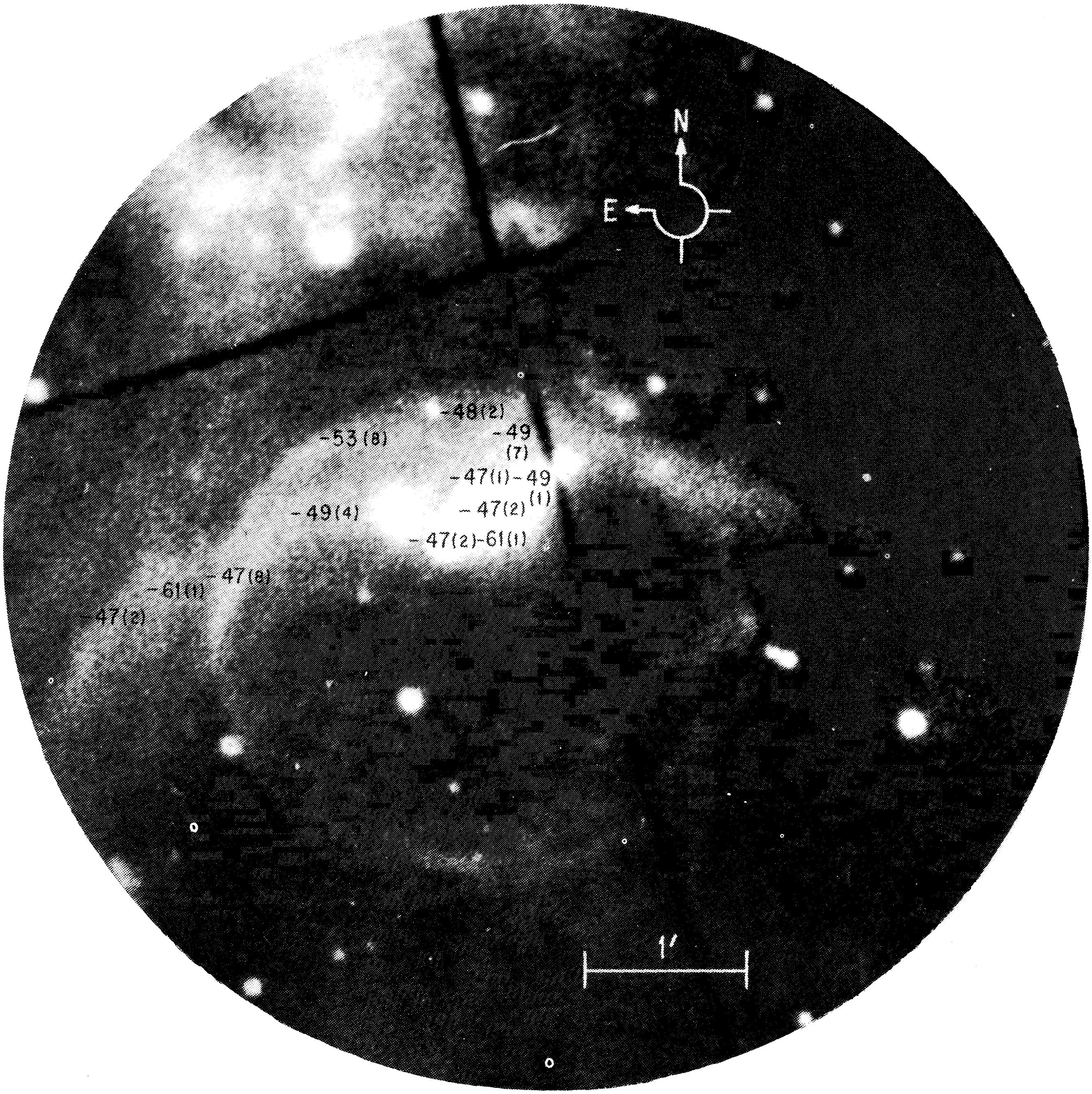

Fig. 8. Enlarged photograph of NGC 7635 with average velocities from the four interferograms (of Table 4) inscribed on it. The direct image is taken with the 2.1-meter reflector.

P. PIŞMIŞ *et al.* (See page 51)