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INTERNAL MOTIONS IN HII REGIONS. I
THE RADIAL VELOCITY FIELD OF NGC 6164-6165.*

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RESUMEN

Usando dos interferogramas Fabry-Pérot, velocidades radiales de la línea Hα en unos 100 puntos han sido obtenidas en la región HII formada por NGC 6164 y 6165. El campo de velocidades es considerablemente complejo, sin embargo, una simetría axial con respecto a la estrella central excitadora HD 148937, O6f, está claramente manifiesta. Las velocidades promedio de NGC 6164 y 6165, de $+20$ y -43 km seg^{-1}, respectivamente, han conducido a la interpretación plausible de que se está observando la expansión del gas eyectado de la estrella O6f. En las fotografías directas se observan condensaciones individuales de marcada simetría con respecto a la estrella central. El resultado novedoso y sorprendente de las velocidades F-P es la existencia, en cuando menos 5 lugares, de pares de puntos vecinos, a distancias del orden de 20″, equivalente a 0.15 pc, en donde la diferencia de las velocidades radiales es de alrededor de 50 km seg^{-1}. Estos puntos corresponden a condensaciones bien marcadas. Se presentan dos modelos tentativos para interpretar las observaciones.

ABSTRACT

On two Fabry-Pérot interferograms, radial velocities from the Hα line at about 100 points in the HII region complex, NGC 6164-6165, are obtained. The velocity field shows considerable complexity, yet, axial symmetry around the exciting star HD 148937, O6f, is clearly present. Average velocities of NGC 6164 and 6165, $+20$ and -43 km sec^{-1}, respectively, lead to the plausible interpretation that one is observing the expansion of gas ejected from the O6f star. Direct photographs reveal a number of blobs with striking symmetry with respect to the central star. The novel and amazing outcome of the F-P velocities is that, at least at 5 different spots two neighboring points at a characteristic distance of 20″, corresponding to 0.15 pc, show a difference in radial velocity of the order of 50 km sec^{-1}; these points normally correspond to well defined blobs.

Two tentative models to account for the observations are presented.

Key words: HII REGIONS — INTERFEROMETRY — RADIAL VELOCITIES

I. INTRODUCTION

The galactic HII regions NGC 6164 and 6165 are symmetrically located with respect to the O6f star HD 148937[+]. This circumstance was noticed by Henize in his survey of planetaries of the southern hemisphere (Henize 1959). The nebular complex —the two bright nebulae, the central star and the fainter nebulae in between—appears in the catalogue of Perek-Kohoutek as a planetary nebula. Westerlund has studied, in some detail, the central star exciting the nebula; his estimate of the visual absolute magnitude, -6.2, leads him to state that the star is too bright to be the nucleus of a planetary (Westerlund 1960). In a recent discussion of this object

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+ R.A. $16^h\ 30^m2$; Decl. $-48°\ .0$ (1950).

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using new data, Johnson (1972) confirms Westerlund's rejection of NGC 6164-6165 as a planetary nebula.

The work reported here is aimed at studying the velocity field in the nebular complex by the Fabry-Pérot technique. While this study was under way, results of an investigation based on slit spectra were published by Catchpole and Feast (1970). They obtained radial velocities at four different points and suggested that the nebulosities were symmetrically ejected from the O6f star. Our Hα emission-line velocities confirm their results and show, further, that there exist large variations in the individual radial velocities over the region of the nebular complex.

II. MORPHOLOGY OF THE NEBULAR COMPLEX

Attention will be directed at this point to some morphological properties which may be relevant to an interpretation of the origin and evolution of the nebulae (see Figure 1 Plate 1).

1. The features that stand out, consisting mostly of condensations, show axial symmetry with respect to the central star. The overall picture resembles an inverted S.

2. NGC 6164 is the fainter of the two and is nearer the central star than NGC 6165. The angles subtended at the star by each nebula are nearly vertex angles. The mass of NGC 6164 may be the smaller of the two.

3. The fainter nebulosities closer to the star (in the bar of the inverted S) show axial symmetry as well, but they are not collinear with the brighter nebulae.

4. In the inner region the nebulosities also exhibit arcs, principally between the star and NGC 6164.

III. THE OBSERVATIONS

The kinematical data presented in this paper are based on two Fabry-Pérot interferograms. Table 1 gives the details of the observational material. Enlarged copies of the interferograms appear as Figures 2 and 3 (Plates 2 and 3).

The measurements on I 361 were performed independently by Mrs. Astier and this author at the Marseilles Observatory and the mean taken; the deviations between the two measurements are not larger than 1 km sec^{-1}. F70 was taken, under very good seeing conditions, with the new Fabry-Pérot equipment at the Cassegrain focus of the 1-meter reflector of the Universidad Nacional Autónoma de México, installed at Tonantzintla. The measurements were performed on the Wild comparator of the CETENAL (Government Surveying Deparment).

No description of equipment and method of reduction will be given here, since a thorough treatment of the method of photographic Fabry Pérot interferometry as developed by Courtès is found in the literature. (see, for example, Courtès 1961, 1972).

TABLE 1

OBSERVATIONAL MATERIAL
FABRY-PEROT INTERFEROGRAMS OF NGC 6164-6165

Plate Number	Basic Instrument	Etalon Interference Order	Filter (half width)	Eastman Kodak Emulsion	Length of Exposure	Date
I 361	150 cm reflector	p = 1060	Hα interference (10Å)	103aE	65 min	April 30, 1970
F 70	100 cm reflector	p = 1060	Hα interference (10Å)	098-01	120 min	May 27, 1973

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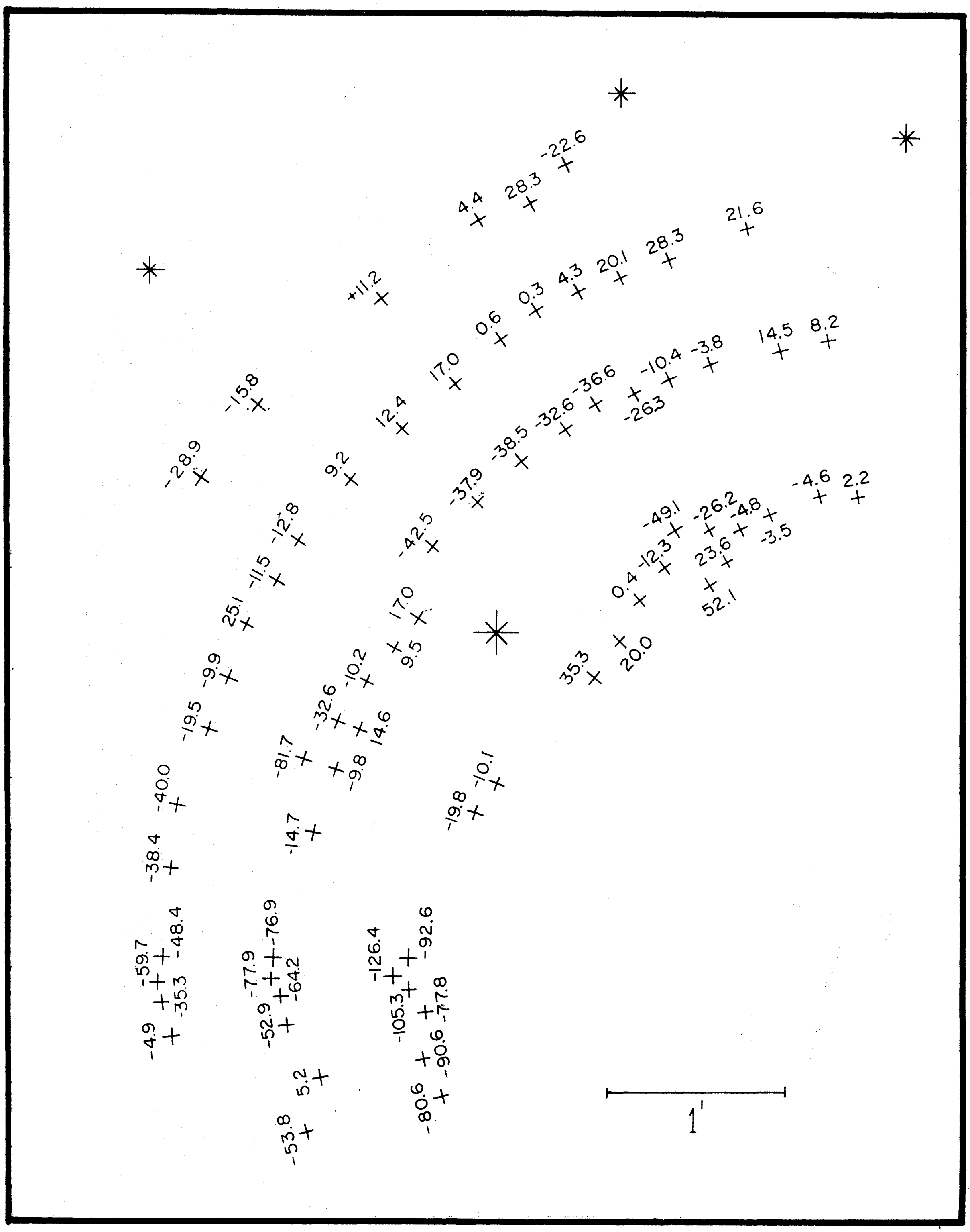

Figs. 4 and 5. The $H\alpha$ velocities in km. sec.$^{-1}$ measured at the marked points from interferograms I 361 and F 70 respectively.

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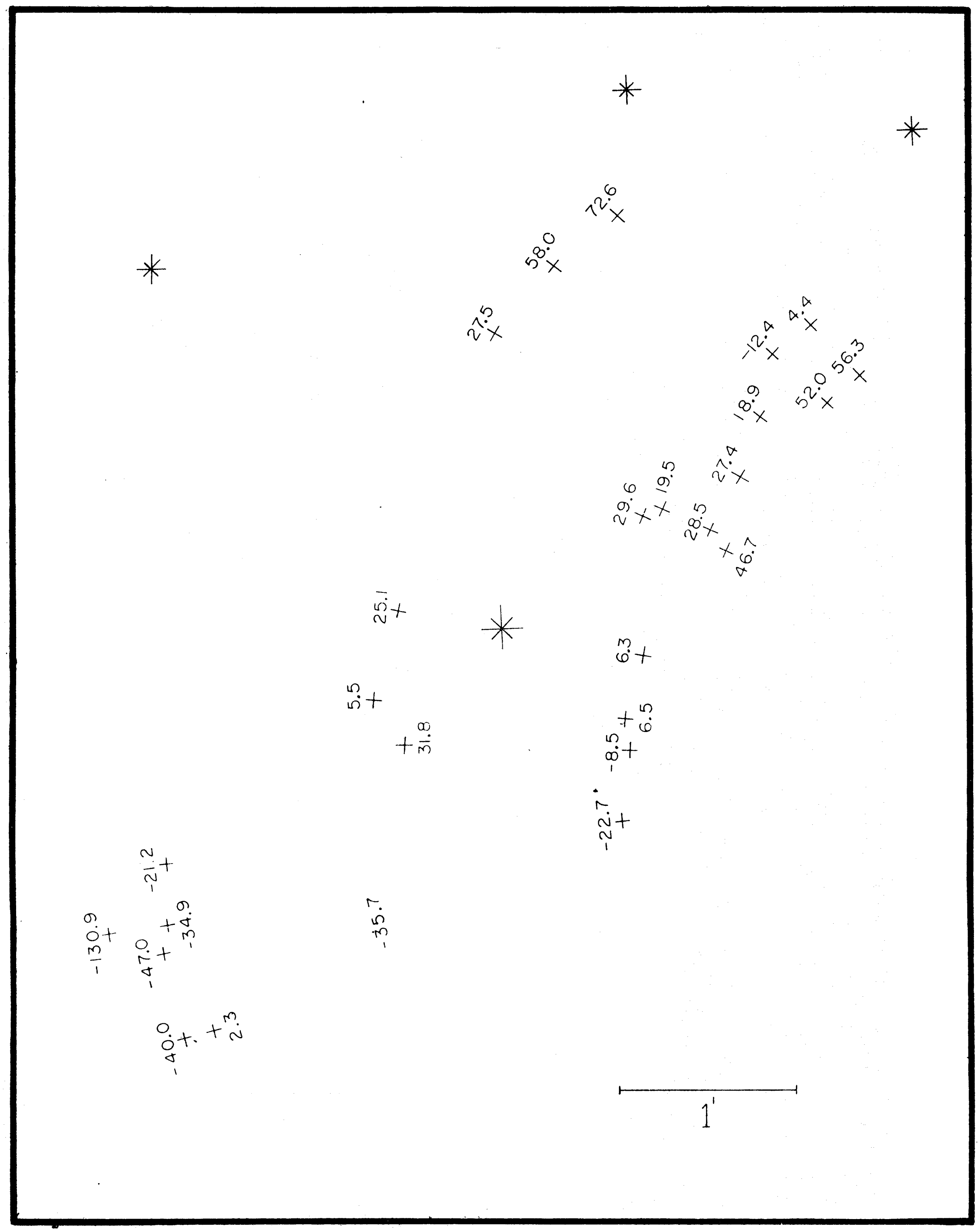

Fig. 5.

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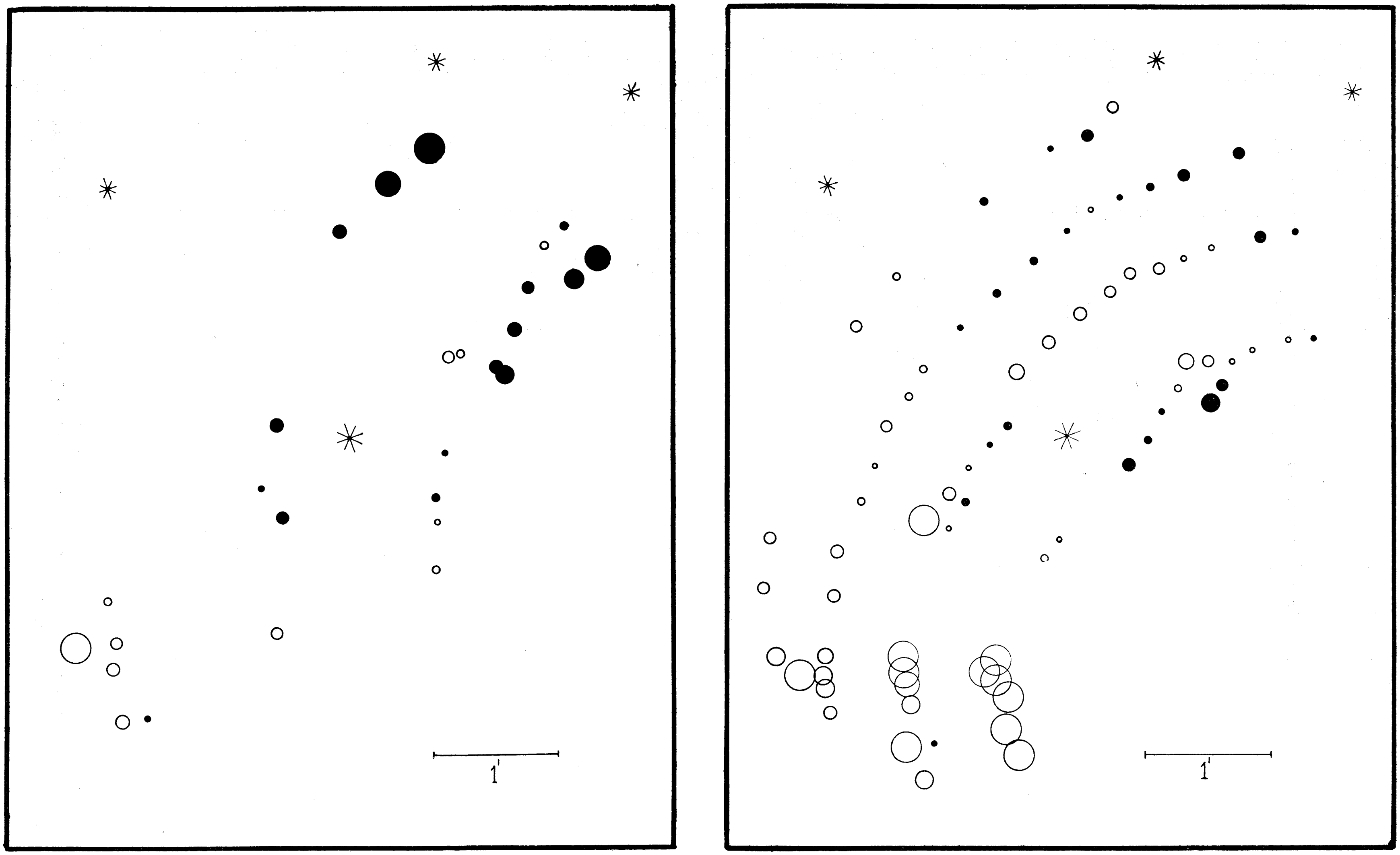

FIGS. 6 AND 7. The same data as in figures 4 and 5 respectively. The radial velocities are grouped into intervals of 10 km. sec.$^{-1}$. The characteristic radial velocity of each interval is represented by a circle with radius proportional to the velocity. Open circles represent negative and filled circles, positive velocities.

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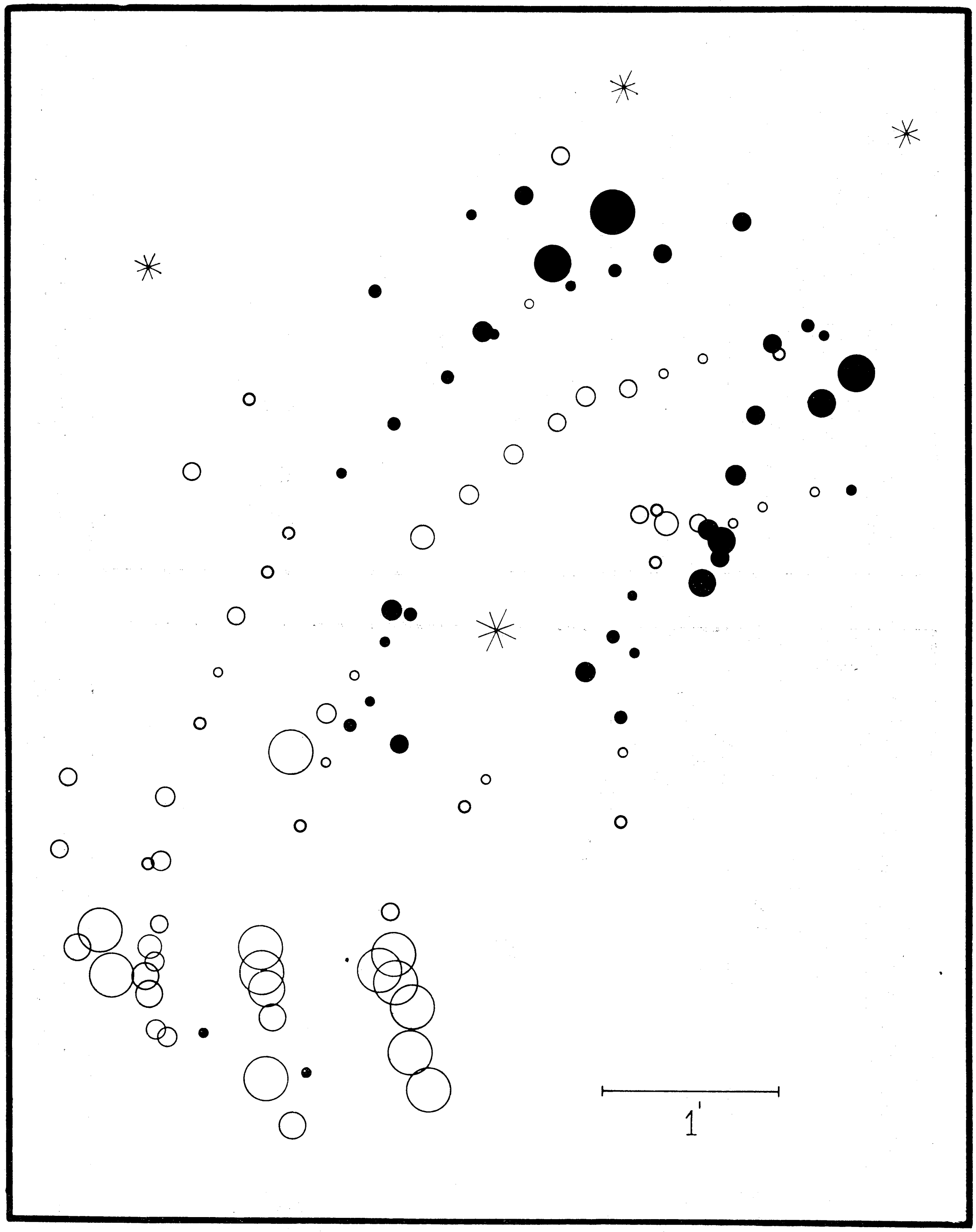

FIG. 8. The data in figures 6 and 7 plotted together. The figure thus represents the complete radial velocity field obtained from the present study.

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IV. THE RADIAL VELOCITY FIELD

The Hα velocities obtained from I 361 and F70 are given in Figures 4 and 5, respectively. The number at each marked point stands for the radial velocity in km sec^{-1} at the point (reduced to the sun). For an overall assessment of the velocity field, the data in the Figures 4 and 5 are given again in Figures 6 and 7 in a different form; here the velocities are grouped into intervals of 10 km sec^{-1} starting from zero; open circles stand for negative velocities, filled circles, for positive velocities. The diameter of a circle is proportional to the representative velocity of each interval. The data appearing in Figures 6 and 7 are combined in Figure 8 which, therefore, is a display of the complete velocity field resulting from the present study.

The complexity of the kinematic features is clearly seen in Figures 6, 7 and 8; at five spots, discontinuities in radial velocity within a small projected distance are undoubtedly present and exhibit axial symmetry with respect to the central star. Some of these discontinuities stand out to even visual inspection of the interferograms, shown in Figures 2 and 3. There are three such regions in Figure 6 and two in Figure 7. Naturally, these discontinuities, five in all, appear also in the combined plot shown in Figure 8. It is worth pointing out that one of these discontinuities which is located nearest to and towards the north-west of the central star happens to fall on both interferograms.

It should be mentioned that a systematic difference may well exist between the radial velocities of the two interferograms, judging from the large positive velocities obtained from F 70 as compared to the velocities from I 361. Again, the complexity of the field hinders a quantitative assessment of such an effect, if it exists. The presentation of the radial velocity data separately for the two interferograms is intended to show that the differences in velocity of neighboring points, the striking outcome of this investigation, are indeed significant, appearing in each one of the interferogram independently and that they do not arise from possible systematic differences in the system of radial velocities of each interferogram.

In the face of the complex velocity field, average velocities of the nebulae may not be too meaningful. For the sake of comparison, however, mean velocities of the brightest parts of NGC 6164 and 6165 are obtained; these are +20 and −43 km sec^{-1}, respectively. The corresponding values given by Catchpole and Feast (1970) are +21 and −43 km sec^{-1} (the position of the slit is not indicated by these authors). The agreement, apparently excellent, may be fortuitous as the standard deviation of the average F-P velocities is ±21 for NGC 6164 and ±34 km sec^{-1} for NGC 6165. The relative radial velocity of the two nebulae is 63 km sec^{-1}; the average line of sight component of the velocity of recession of NGC 6164 and 6165 from HD 148937 will be adopted as 32 km sec^{-1} (Catchpole and Feast 1970).

Again, due to the complexity of the field, it has not been possible to find a unique value for the motion of the centroid of the system. On the one hand the radial velocity of the O6f star, of which the spectral lines show P Cygni characteristics, cannot be determined reliably. On the other hand, nor can the velocity of the system be uniquely obtained from considerations of symmetry: the velocity of the system based on the NGC 6164-6165 proper is −11 km sec^{-1}, while that determined from the inner symmetrical nebulae is ≃ −5 km sec^{-1}. A similar situation is presented by the slit radial velocities of Catchpole and Feast. We have, therefore, preferred to discuss the kinematics of the nebular complex without reference to the centroid.

V. DISCUSSION OF THE VELOCITY FIELD

The apparent expansion of the nebular complex and the symmetrical arrangement of the blobs of Hα emission leave little room to doubt that the main ejection of matter from the O6f star has taken place in pulses from two nearly diametrically opposite regions. The inner and fainter nebulosities appear to be ejected with lower velocity and presumably at a later time. Ejection may still be continuing.

We emphasize once again that the novel feature that has emerged from our Hα velocities is the large relative velocity at neighboring points in the nebular complex. In three of these points the differences of velocity are associated with well defined blobs. In Figure 9 the main condensations of the region are schematically shown. As an illustration,

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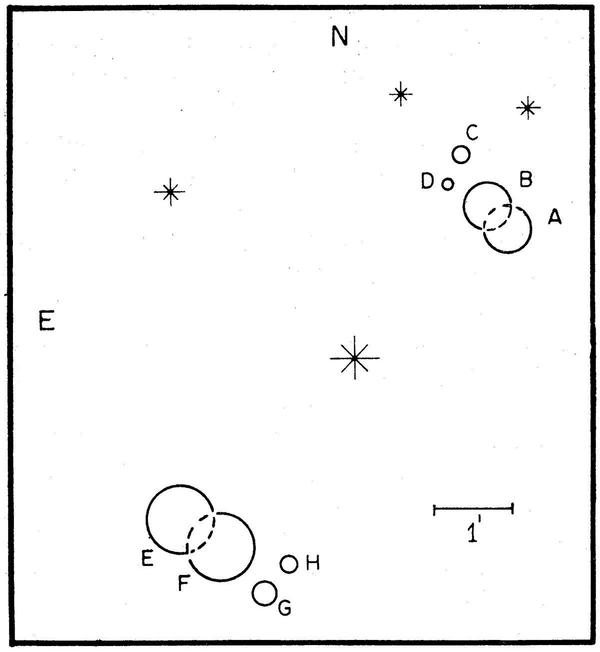

FIG. 9. A schematic representation of the well-defined regions of the nebular complex NGC 6164-6165.

only the conspicuous blobs will be discussed. The pair of blobs designated by A and B in NGC 6164 have radial velocities of +54.3 and +1.4 km sec^{-1} indicating that A is receding relative to B along the line of sight by 52.9 km sec^{-1}. The corresponding blobs in NGC 6165, E and F, have radial velocities of −40.6 and +9.3 km sec^{-1}; hence a relative line of sight component of nearly 50 km sec^{-1}, indicating that E (the counterpart of A) is approaching while F (the counterart of B) is receding. The smaller blobs in NGC 6165, G and H, move with a radial velocity of −53.8 and +5.2 km sec^{-1}, respectively. The radial velocity of C in NGC 6164 is +14.6 km sec^{-1}; of the neighboring blob D no velocity is obtained as it did not fall on an interference ring.

VI. ATTEMPT TOWARD INTERPRETATION

It has not been possible, so far, to advance a unique model for this object which satisfies equally well the morphological and kinematical properties mentioned earlier. In general, it appears plausible that the masses forming the HII complex are ejected from the ends of a diameter of the O6f star and that this direction of ejection is slightly inclined (10° seems to be the best fit) to the plane of the sky. The average velocity of recession of NGC 6164 and 6165 from the central star is, then, 184 km sec^{-1}. If we adopt average values for the mass and radius of the star, 33 solar masses (Catchpole and Feast 1970) and 33 solar radii (Underhill 1971), the velocity of ejection at the star is about 650 km sec^{-1}, far larger than the escape velocity.

Two schematic models will be briefly presented; in both models the agent funneling the ejecta is presumably a magnetic field, a dipole, along the direction of ejection.

Model 1. The rotation axis of the central star is assumed to be inclined to the projection plane by 10°, while the ejecting diameter makes an angle of 15° with the axis of rotation (Figure 10). Matter is ejected in pulses while the star rotates. Two apparently neighboring condensations may result from ejections while the active region is on the side of the rotation axis nearer the observer and the next one, when the region has moved to the farther side of the axis. Moreover, an approaching blob will have its receding counterpart in the other nebula. The model explains the kinematical data in a natural way. A morphological consequence of this mechanism is that in NGC 6164 the receding condensation should appear in projection closer to the central star than the approaching one. Thus, the two blobs A and B which show a velocity difference of 52.9 km sec^{-1} should not be at the same projected distance from the central star as observed (see Figure 10). The difference should be about a tenth of the distance to the central star. Furthermore, the two small condensations which show a difference in radial velocity of 59 km sec^{-1} are located inversely to what the model predicts. Unless one assumes different velocities of ejection at different times of apparently similar condensations, this attractive model seems inadequate.

Model 2. In this model again the direction of ejection, the dipole, makes an angle of about 10° with the projection plane but the axis of rotation is assumed to be close to the line of sight (Figure 11). This constraint stems from the existence of circular arcs which are also roughly concentric with the star.

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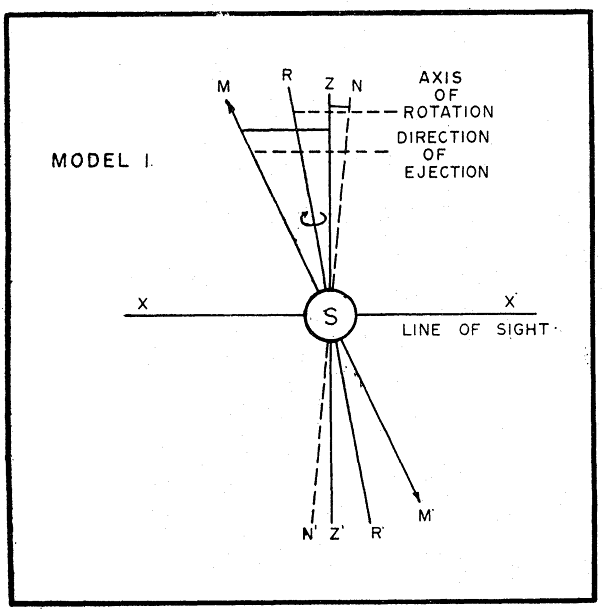

FIG. 10. Schematic representation of model 1 in two dimensions; the upper part represents the case for NGC 6164, the lower part that for NGC 6165.

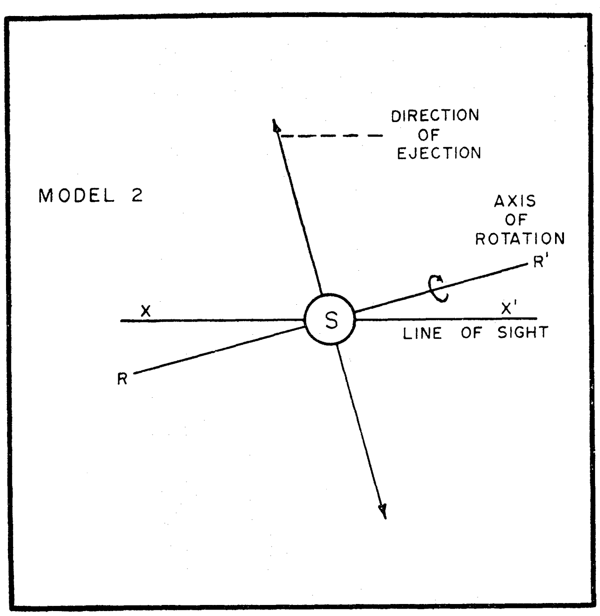

FIG. 11. Schematic representation of model 2 in two dimensions. The plane of the paper, as in Fig. 10, contains the line of sight and the axis of rotation.

The emitting diameter, then, is either on the equator or very close to it. The ejection is, again, presumed to be in pulses along magnetic lines of force. It is interesting to mention that Ozernoi and Usov (1971) have shown, on theoretical grounds, that "under certain conditions a rotating magnetic star may shed matter in pulses". All morphological properties can be reasonably accounted for by this model. The only vulnerable point is that to explain the difference in radial velocity of two neighboring points, one needs to introduce the hypothesis that two blobs of gas are ejected from the same region at nearly the same time in different directions. Physically, this may be a difficult requirement to explain. However, it is conceivable that vorticity at the ejection points may help such a phenomenon to take place. This model will have no difficulty in explaining the fact that the fainter inner regions are not collinear with the main nebulae. Presumably they are ejected at a later epoch and at a different orientation of the ejection point with respect to the observer.

If we assume the velocity of rotation of the parent star to be 300 km sec^{-1} at the equator, the main burst giving rise to NGC 6164 and 6165 proper will have occured in an interval of about 15 hours. The time elapsed since the ejection started from the star, expansion age, is found to be 4.4×10^3 years in either model for a distance of 1.5 kpc for the system, while the age estimated from a characteristic separation of the condensations of 20″ and for a relative characteristic velocity of 50 km sec^{-1} is 4×10^3 years. No determination of mass is available as yet but if the total mass in the nebulae NGC 6164-6165 ejected from the parent star is 0.5 solar masses, with the assumed physical parameters of the star (650 km sec^{-1} velocity of ejection), the main detonation would require 4×10^{48} ergs of energy.

VII. THE SURROUNDINGS OF THE NEBULAR COMPLEX

Farther out from the complex NGC 6164-6165 there exist nebulosities which seem to be related to the former object. Westerlund (1960) has given a description of these nebulosities, briefly as follows: there is an arc of 13′ to the northeast of the Of star and a circular faint nebula, presumably the projection of a shell, with maximum and minimum distance from the Of star of 44′ and 64′, respectively. This bright ring is surrounded by an apparent ring of dust. These features are more conspicuous in the reproduction by Johnson (1968) of Westerlund's photograph.

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The central position of the Of star with respect to the HII complex NGC 6164-6165 and to the outer nebulae, in particular to the outermost, nearly circular ring, suggests strongly that all of these are physically related to one another, perhaps the outcome of instabilities undergone by the central star at different epochs. The outermost ring may well be a supernova remnant. It is better defined and more conspicuous than the Monoceros remnant which appears in the Atlas published by van den Bergh, Marscher and Terzian (1973). It may be worthwhile to search for more decisive lines of evidence, by radio data for example, to decide whether this ring is, indeed, a supernova remnant or not.

Further observations of this region, both interferometric and spectroscopic, will be resumed shortly.

This paper is the first report of investigations being carried out on the internal motions in galactic HII regions with our new Fabry-Pérot equipment in use since late 1972, at the 1-meter telescope of the Universidad Nacional Autónoma de México. The Fabry-Pérot apparatus is the outcome of the cooperation of our colleagues at Marseilles Observatory. Thanks are due Drs. Courtès, Monnet, Georgelin, and above all, Engineer di Biagio, who coordinated and supervised the construction of the focal reducer. It is also a pleasant duty to acknowledge the hospitality of the astronomers at Córdoba Observatory, Argentina; to Dr. Carranza goes my sincere appreciation for collaboration out of which plate I 361 has emerged. Last, but not least, I am indebted to my Mexican colleagues, in particular to M.A. Moreno for efficient assistance at the telescope and to Mrs. Ilse Hasse for the reductions.

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