Revista Mexicana de Astronomía y Astrofísica, Volumen 2, Agosto 1977

INTERNAL MOTIONS IN H II REGIONS. IV. THE RING NEBULA NGC 2359

PARIS PIȘMIȘ, ELSA RECILLAS-CRUZ
AND ILSE HASSE

Instituto de Astronomía
Universidad Nacional Autónoma de México
Received 1977 January 3

RESUMEN

Por medio de cinco interferogramas Fabry-Pérot, se ha determinado la velocidad radial de la línea Hα en 338 puntos en la nebulosa anular NGC 2359 y en su vecindad. La velocidad promedio de la totalidad de la región H II es de +71.0 ± 7.5 km s^{-1}. Este valor se ha tomado como la velocidad radial de la estrella WN5 HD 56925 la cual es la fuente de la excitación de la región H II. Usando el modelo de Schmidt, la distancia cinemática al objeto es de 4.0 kpc. El campo de velocidades muestra una estructura claramente asociada a la morfología de la región. Es interesante hacer notar la presencia de dos filamentos elípticos que rodean a la estrella excitadora; la velocidad promedio de los filamentos interior y exterior son de 84 ± 5 y 56 ± 7 km s^{-1} respectivamente mostrando claramente, que con respecto a la estrella, el anillo exterior se aleja mientras que el anillo interior se acerca al observador. Esta peculiaridad apoya al modelo que se sugiere para la eyección de material que ha ocurrido en forma no isotrópica sino en regiones localizadas en hemisferios opuestos de la estrella WN5 en rotación, cuyo eje de rotación coincide aproximadamente con la dirección de la visual. Se sugiere que la pérdida de masa de la estrella WR central actualmente puede ocurrir también en dos regiones casi diametralmente opuestas sobre la superficie de la estrella.

ABSTRACT

On five Fabry-Pérot interferograms radial velocities from the Hα line at 338 points on and around the "ring" nebula NGC 2359 have yielded +71.0 ± 7.5 km s^{-1} for the mean overall velocity of the H II region. This value is taken to represent the radial velocity of the WN5 star HD 56925, the source of the excitation of the H II region. Using the Schmidt model the kinematic distance of the object is 4.0 kpc. The velocity field has structure clearly related to the morphology of the region. Attention is concentrated on two well defined elliptical filaments around the exciting star. The mean velocities of outer and inner filaments are 84 ± 5 and 56 ± 7 km s^{-1} respectively showing clearly that with respect to the star the outer ring is receding while the inner one approaching the observer. This peculiarity is strong support to the model we suggest that the ejection is essentially non-isotropic, and it has occurred in localized regions on the opposite hemispheres of the rotating WN5 star with axis of rotation close to the line of sight. It is suggested that the central WR may also follow at present a similar pattern of mass loss from nearly diametrically opposite spots on the star.

Key words: H II REGIONS — INTERFEROMETRY — RADIAL VELOCITIES.

I. INTRODUCTION

Several filamentary galactic nebulae presenting a ring structure are known to exist in association with Wolf-Rayet stars. The rings are often referred to as "shells". Johnson and Hogg called attention to this class of objects and made a study of a few of these (Johnson and Hogg, 1965). Their discussion of optical and radio continuum data led them to suggest that NGC 2359 (S 298) had evolved from the interaction of the gas, ejected from the Wolf-Rayet star, with the surrounding interstellar matter which is swept up by the ejecta.

Lozinskaya has discussed the kinematics of NGC 2359 based on the dispersion of velocities obtained from the half-widths of the interference pattern in Hα, using Fabry-Pérot interferograms. The results are interpreted as evidence for an expansion of the ring structure (filamentary shell) at a rate of 55 ± 25 km s^{-1}. This result presumably supports the theoretical model proposed by Pikel'ner and Shcheglov (1969) and by Avedisova (1971): that these ring structures are caused by the interaction of stellar wind with the surrounding interstellar matter. But the large dispersion 100 − 200 km s^{-1} found by Lozinskaya is not explained by this mechanism (Lozinskaya 1973).

In this paper we present a detailed velocity field of NGC 2359 obtained from Fabry-Pérot interferometry. We also detect an expansion of the filamentary structure; further, our data permit a more detailed kinematic study of the ring structure. We find that the outer ring is receding and the inner one is approaching the observer and propose a model where the ejection from the parent star is non isotropic.

II. DESCRIPTION OF THE H II REGION

NGC 2359 has an extension of roughly 20 arc min. The densest central part roughly 4×4 arc minutes shows a structure essentially of filaments, surrounding the WN5 star HD 56925, which is evidently the source of the excitation of the nebula. Three fainter extensions starting from the ring system, stretch out to a distance of $\simeq 10$ arc min from the central star. Figure 1 (Plate 6) is an enlarged copy from the Palomar Sky Survey red print of the region and Figure 2 (Plate 7), an enlargement of a plate taken with a focal reducer through a 10Å interference filter at Hα.

III. OBSERVATIONS

Five interferograms constitute the observational material on which this work is based. These were obtained with a focal reducer attached to the 1-meter reflector of the University of Mexico installed at Tonantzintla. The 10Å halfwidth interference filter isolates the Hα line. The étalon, with p = 1060 as the highest interference order, gives an interorder separation of 283 km s^{-1}. The calibration for zero radial velocity is done by means of a hydrogen lamp interferogram taken before and after the field exposure. Three of the interferograms were taken directly on photographic plates (scale 3.1 arc min mm^{-1}) and the remaining two, through a Varo one-stage image tube (scale 1.5 arc min mm^{-1}). A sample interferogram F 171 is reproduced in Figure 3 (Plate 8) which should give an idea of the quality of material used in the present study. The data relevant to the observations are given in Table 1.

The interferograms were measured on the Mann comparator at the NASA Johnson Space Center. The polar coordinates at the maximum intensity point of all significant details on the interference rings were measured and their Doppler shifts obtained by comparison with similar measurements of the hydrogen calibration interferograms. The data punched on cards were processed at the Computer Center of the University of Mexico with a program adapted to the reduction procedure given by Courtès (1960).

TABLE 1

OBSERVATIONAL MATERIAL

Plate	1975 α	1975 δ	Exposure	Emulsion	Date
F 168	7 17°13.′0	; − 13°10.′5	3 hrs	098–01	1975 Feb 2
F 169	7 17 4.5	; − 13 9.4	3:30 hrs	098–01	" March 3
F 171	7 17 5.5	; − 13 9.5	3 hrs	098–01	" March 5
FI 239	7 17 5.5	; − 13 9.5	38 min	103aG	1976 April 2
FI 240	7 17 22.0	; − 13 12.5	30 min	103aG	" April 5

The last two interferograms are taken through an image tube.

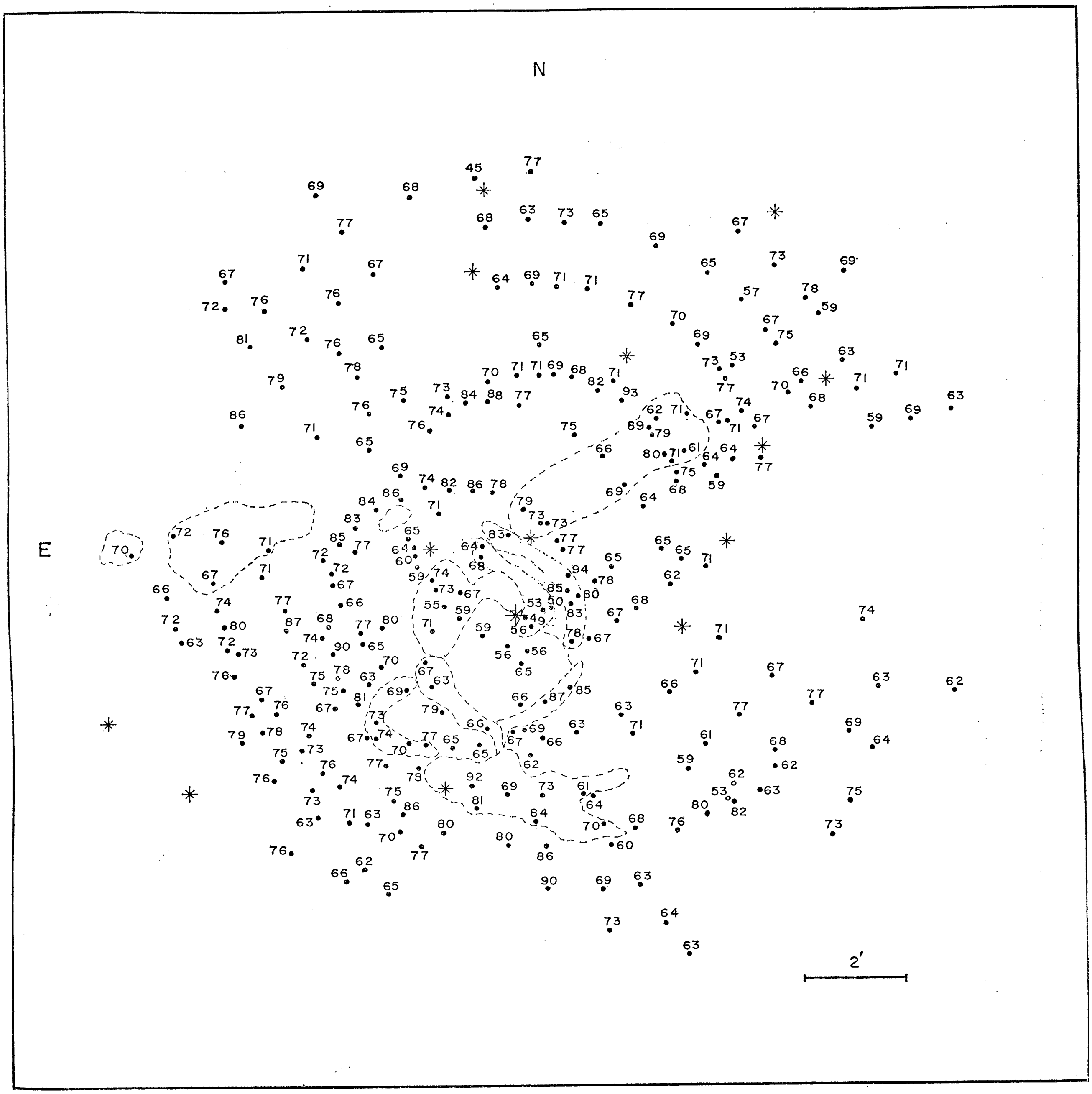

FIG. 4. Velocities averaged over neighboring points of NGC 2359. In the two filamentary regions marked f_1 and f_2 in Figure 5, the indicated radial velocities are individual values from different interferograms.

IV. THE GENERAL VELOCITY FIELD

Radial velocities at 338 points were determined in the manner described above from all five interferograms. It has seemed to us unnecessary to display these velocities individually; instead we have combined values at neighboring points, 2, 3 or 4 in number, assigning an average velocity at the midpoint of the assembly. The characteristic dimension of these regions is less than 6 arc sec corresponding to 0.1 pc at the distance 4.0 kpc of the nebula. Figure 5 gives the average velocities. To serve as a reference a few of the brightest stars are also indicated. All velocities are referred to the sun and not to the LSR. The mean radial velocity of all measured points (338 points) yielded 71 ± 7.5 km s^{-1} (standard deviation) and this is adopted as the radial velocity of NGC 2359 as well as that of the exciting WR star of which no radial velocity is known.

A subdivision of NGC 2359 following its well-marked features appeared to us instructive; the subdivisions are marked in Figure 4 by broken lines. Figure 5 shows once again a sketch of the subdivision scheme where the mean radial velocities with standard deviations are indicated for each of the delineated features.

The mean motion of all the features taken together is 70.5 km s^{-1} (62 points) and of the regions outside of these, it is 71.1 km s^{-1} (276 points); both values are in excellent agreement with the overall average radial velocity. This circumstance shows that the ring-like features and the fainter regions are spatially coincident and that 71.0 km s^{-1} represents very reliably the average motion of the entire NGC 2359. However it is noteworthy (see Figure 5) that the inner features, 5 in all, show radial motions systematically less than that of the centroid of the

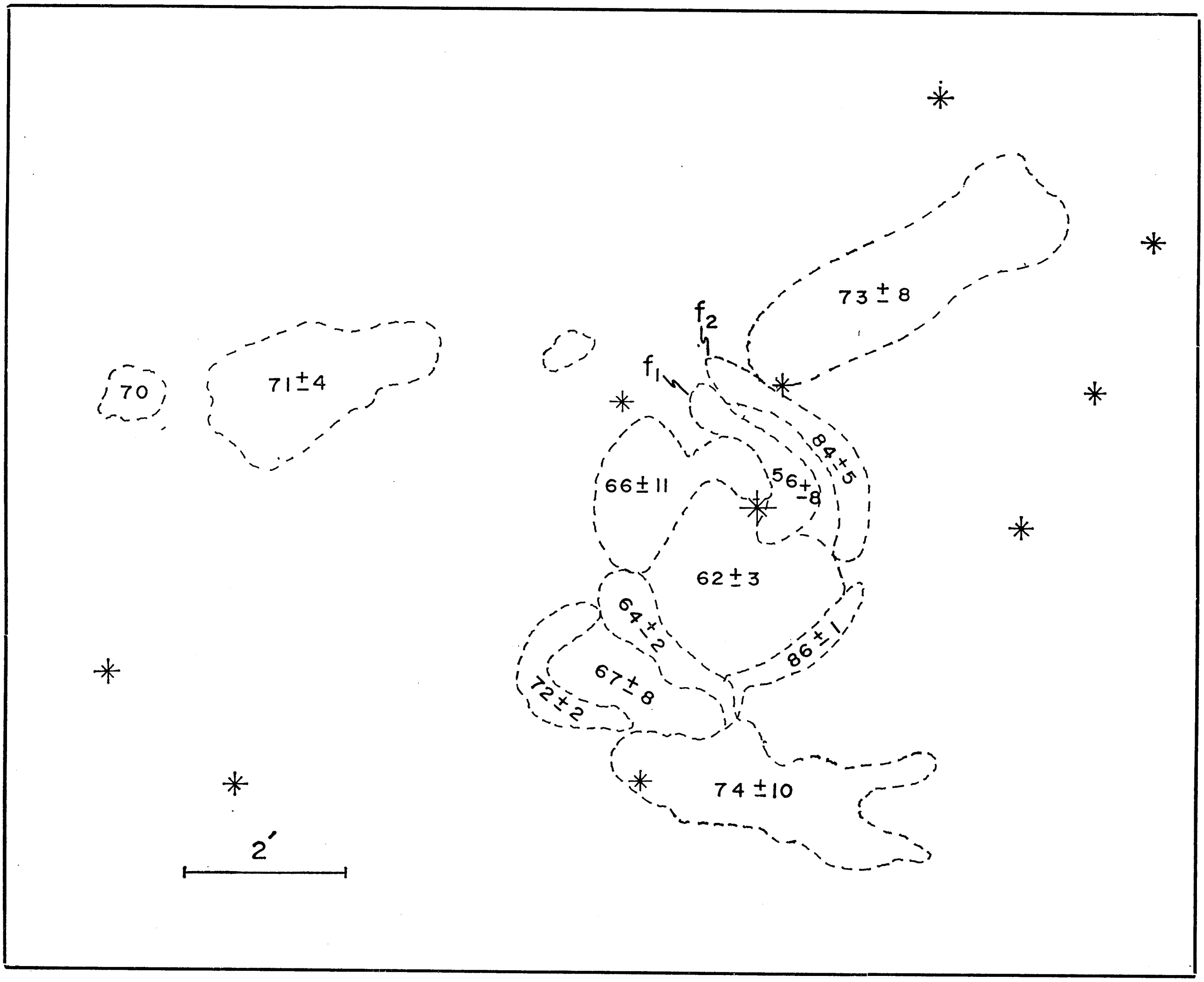

FIG. 5. The scheme of the subregions as in Figure 4. The mean velocities with their standard derivations are inscribed in each of the subregions.

omplete H II region while the seven peripheral ɜatures have velocities systematically larger than 1.0 km s^{-1} (except for a small region with one ıeasured point). Thus the set of inner filaments is pproaching the observer at a velocity of 8 km s^{-1} nd the peripheral set is receding at 4 km s^{-1}. This ıdicates that both sets are moving away from the entral star and in nearly opposite directions. Par-cularly striking is the velocity difference shown by he two concentric sectors of the ring-shaped filaments esignated by f_1 and f_2 in Figure 5. These two fila-ıents will be taken up below for a more detailed iscussion.

V. THE STANDARD DEVIATIONS

Our procedure of evaluating the interferograms loes not take into account the profile or the width of the interference rings and therefore does not rield the dispersion of the velocities at the given point. Although an idea can be had of the disper-ion by inspection of the width of the rings, a quantitative value can be obtained only through calibrated surface photometry. Our data thus give only the average velocities of all the matter in the ine of sight through the points. The dispersion or he width of the interference pattern, aside from nstrumental, may be caused by temperature broad-ening, through turbulence, expansion or contraction. The first two are likely to cause symmetrical profiles and thus will not affect the average velocities. If there is expansion (or contraction), and if this is spherically symmetrical, for an optically thin nebula the measured velocity will indeed represent that of the assembly. However if the nebula is optically thick the central regions will show asymmetrical profiles and our observed velocities will be shifted to the violet. In the general background we have not noted a difference of radial velocity from the center of the nebula outwards. If indeed expanding, the nebula must be optically thin.

The standard deviation we can obtain from our material is that of the mean velocities in specific areas of the H II region; our standard deviations are typically 7 km s^{-1}. Mean radial velocities of H II regions studied by Courtès (1960), Georgelin and Georgelin (1970), Pişmiş and Rosado (1974), and Pişmiş and Moreno (1976) show that standard deviations are usually in the range 3 to 9 km s^{-1}. These values may involve two effects. 1) A spurious effect due to the deviation of the line of sight velocity from the real one caused by the convolution of the interference pattern with the irregularities in the light distribution of the H II region, and 2) a physical effect, arising from small scale irregularities in the average motion of the column of gas projected at neighboring points. A cursory inspection of the list by Georgelin and Georgelin (1970) of galactic H II region velocities shows that a smooth distribution of Hα gives a small standard deviation of the average velocity; on the other hand turbulent mass motions are also expected to be small in regions of smooth morphology. Both effects increase with increasing irregularity of the field. It is therefore not possible to decide as to which of these effects is operative without carrying out a deconvolution of the interferograms.

Lozinskaya's investigation,, (Lozinskaya 1973) of NGC 2359 is based on the profiles of the interference pattern from which she obtains the dispersion of the radial velocities. The mean width of the Hα line emitted in the filaments of NGC 2359 corresponds to 150-200 km s^{-1}. It is concluded that this H II region is expanding at a rate of 55 ± 25 km s^{-1}. These conclusions do not seem to be tenable according to our data. Lozinskaya further states that the velocity field of NGC 2359 shows a great deal of structure —with which we agree— but no individual velocities are given or discussed in that paper.

VI. THE EXCITING STAR

All seven ring nebulae known to date are associated with WN stars. Information concerning HD 56925, the central star of NGC 2359 is rather scanty. Table 2 summarizes its physical parameters relevant to the present study.

VII. THE DISTANCE OF THE H II REGION

We have computed the kinematic distance of NGC 2359 on the basis of the Schmidt rotation curve and the assumption that the observed radial velocity of 71.0 km s^{-1}, after eliminating the solar motion com-

TABLE 2

DATA RELATED TO HD 56925

Coordinates	α: $7^h17^m13^s$	δ: 13°10′5		(1975)
	l: 227°8	b: −0°1		
Spectrum		WN5	(1)	
$v(\frac{1}{\lambda_v} = 1.94)$		11.74	(1)	
$b - v(\frac{1}{\lambda_b} = 2.34)$		+0.33	(1)	
M_V		−4.3	(1)	
		−3.1	(3)	
		−3.7	(2)	
T_e		53000°K	(4)	
Mass		10 $M_\odot$	(5)	
Distance kpc		6.9	(6)	
		4.0	(7)	

(1) Smith, L. F. 1968, *M.N.R.A.S.*, **138**, 109.
(2) Crampton, D. 1971, *M.N.R.A.S.*, **153**, 303.
(3) Computed using a kinematic distance of 4.0 kpc obtained in this paper.
(4) We have adopted this value assigned to 50896, also a WN5 star, by Smith (1).
(5) This is an average value over the range 6-15 solar masses given by Underhill 1973, *Wolf-Rayet and High Temperature Stars*, ed. Bappu and Sahade, p. 237.
(6) Smith, L. F. 1968*c*, *M.N.R.A.S.*, **141**, 317.
(7) kinematic, this paper.

ponent of −18.0, is solely due to differential rotation (53.0 km s^{-1}). The distance thus obtained is 4.0 kpc which we adopt as the distance of the nebula. This is to be compared with the photometric distance of the WN5 star, 6.9 kpc, given in Table 2. That there is a discrepancy between the kinematic and photometric distances of H II regions has been a standing problem. Such discrepancy if not a real physical effect (Minn and Greenberg 1973) may arise from either inadequate assumptions involved in the kinematic distance determination or in the photometric distance determination of the exciting star. The vulnerable points in the first case are 1) the assumption that the H II region is describing a circular orbit and 2) that the Schmidt curve is the adequate one. The discrepancy appears to be by far the more pronounced in the anticenter direction suggesting that the rotation curve may be flatter at the maximun beyond the sun compared with the Schmidt curve. For a more detailed discussion of the problem we refer to a paper by Pişmiş and Moreno (1976).

In the second case the objectionable assumptions are the absolute magnitude and intrinsic color calibrations of the WN5 star. We mention in passing that the photometric distance would reduce to 4.0 kpc, equal to the kinematic distance obtained above if the absolute magnitude of the star were −3.1 instead of −4.3 as obtained from the calibration by Smith (1968*a*). On the other hand Crampton's calibration (Crampton 1971) gives −3.7 for the absolute magnitude of a WN5 star. There is thus indication that the absolute magnitudes of WR stars are probably lower than the values obtained from existing calibrations.

Georgelin and Georgelin's estimate from 29 points gives +74 km s^{-1} as the radial velocity of NGC 2359 (Georgelin and Georgelin 1970). This is higher than our value of 71.0 but comparable to our velocity of the southern denser region of this object. Given the large number of measured points (338) from which our mean velocity of NGC 2359 is obtained we expect our value and the kinematic distance of the object derived from it to be more reliable than previous estimates.

VIII. A MODEL FOR THE FILAMENTARY FEATURES

The filamentary structure not only in the periphery but also across the face of NGC 2359 makes it quite unlikely that the ejection from the star has been isotropic. This belief is strengthened by the velocity structure of particularly the peripherial filaments denoted by f_1 and f_2 (Figure 5). Were these features projections of a spherical (or spheroidal) shell their velocities would be that of the central star or of the H II region at large. It can be deduced from Figure 5 that the radial velocity of the outer filament f_2, is +13 km s^{-1}, and that of f_1, the inner filament −15 km s^{-1}, relative to NGC 2359 as a whole. As these two filaments have the best determined velocities the confrontation of model with observation will be made through these features. To give an idea of the reliability of our data within filaments f_1 and f_2 we have given in Figure 4 individual values of the velocities at the marked points, obtained from different interferograms, instead of averages.

The model which appears to us quite plausible is the following: Gas was ejected *t* years ago from localized regions on a fast rotating star with axis of rotation close to the line of sight. Filament f_1, ejected from a spot on the stellar hemisphere facing the observer, is at present seen as the projection of the (helically) approaching gas; while filament f_2 ejected from a spot on the opposite hemisphere is seen as the projection of the (helically) receding gas. In either case one is probably witnessing the shock front caused by the ejected gas plowing into the surrounding material. Figure 6 shows the geometry of the model. The ejection may have taken place at different epochs and with different velocities. But if we assume that they ocurred almost simultaneously and with equal initial speed certain interesting conclusions can be reached.

In Figure 6 the circle represents the surface of the star. The line of sight, in the plane of the paper, is vertically upward. This line also defines the projection of the rotation axis which is assumed to be close to the line of sight. The ejecting areas are around the points A_1 and A_2. Let V = the speed of ejection from both A_1 and A_2, $\overline{O_1A_1}$ and $\overline{O_2A_2}$ the distances of the ejecting areas to the line of sight and α_1 and α_2 the angles which V makes with the line of sight at A_1 and A_2 respectively. We also assume that the interaction of the ejecta with the ambient interstellar material, i.e., deceleration, for both ejecta has been comparable. Under these circumstances Figure 6 also represents the situation of the ejecta t years after the ejection, if scaled to the observed dimensions of the filaments at time *t*. The tangential velocities of the ejecta will therefore be proportional to $\overline{O_1A_1}$ and $\overline{O_2A_2}$ respectively. It may be argued that our estimate of $\overline{O_1A_1}$ and $\overline{O_2A_2}$ corresponds to features produced by the ejecting areas with a lag of half a period of rotation. But on a fast rotating star, if we believe a WR star to be, half a period or even a complete period of difference will not introduce a perceptible error. The model does not specify the relative azimuthal angle of A_1 and A_2. But physically it seems more likely that they are situated as we have drawn in the sketch, near the ends of a diameter. From the direct photograph we estimate, along the apparent "major axis" of the rings, that

$$\overline{O_2A_2} = 1.5\,\overline{O_1A_1}\,.$$

Then, if

$$V_T(A_1) = x$$

we have

$$V_T(A_2) = 1.5\,x$$

where x is in km s^{-1}.

On the other hand

$$V_r(A_1) = 15 \text{ km s}^{-1} \text{ and } V_r(A_2) = 13 \text{ km s}^{-1}\,.$$

With these values and the equality of V at both A_1 and A_2 we obtain a second degree equation in x, a solution of which gives x = 6.69 km s^{-1}. Thus

$$V_T(A_1) = 6.69 \text{ km s}^{-1},\ V_T\ (A_2) = 10.04 \text{ km s}^{-1},$$

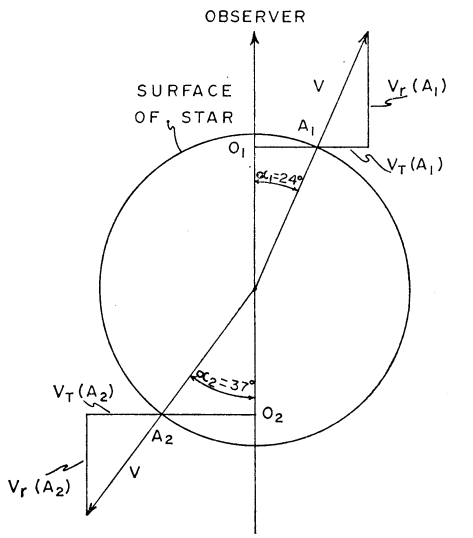

FIG. 6. Sketch representing the model proposed in the present study to explain the ring structure and its velocity field.

and therefore the velocity of expansion at present is $V = 16.43$ km s^{-1}. With the latter value we can compute the velocity with which f_1 or f_2 were ejected from the star. We adopt 10 $M_\odot$ for the mass of the WN5 star as given in Table 2 and a rough value for the radius as 6.0 $R_\odot$; the latter is estimated assuming that the star radiates like a black body with effective temperature 53000°K (Smith 1968a) and with $M_{bol} = -8.9$. We then obtain the velocity of ejection from the star as 800 km s^{-1}. The angles α_1 and α_2 are found to be $\simeq 24°15'$ and $37°40'$ respectively; hence the ejecting regions are not far from the ends of a diameter of the star.

The time t of ejection from the star can now be estimated. Either one of the two filaments, f_1 or f_2, can be used for the purpose: we choose f_2. For a distance of 4 kpc of the H II region the distance of f_2 from the star is 3.66 pc based on a projected distance of f_2 from the star, of 2.1 arcminutes. Further, the average speed with which matter reaches the distance 3.66 pc is adopted as 32 km s^{-1} which is the harmonic mean of the speed of ejection (800 km s^{-1}) and the present speed, 16.43 km s^{-1}. With these values we find that the ejection from both A_1 and A_2 has taken place $\simeq 1.2 \times 10^5$ years ago. To compute this age we have assumed the distance of NGC 2359 to be 4.0 kpc. Should the photometric distance, 6.9 kpc, be the correct one, our model and the physical parameters derived from it will remain invariant. The only significant change will be in the linear distance traveled by the ejecta in particular of areas f_1 and f_2. Consequently the age estimated above will be larger by the factor 6.9/4.0; thus the age of the ejection will be 2.1×10^5 years.

In computing the velocity of ejection the assumption is implicit that the deceleration of the ejected gas is only gravitational. Doubtless the expanding material has undergone braking due to interstellar matter, an effect quite impossible to assess at the moment. The computed velocity of ejection may therefore be an underestimate; consequently the age will be slightly overestimated. We note in passing that Lozinskaya's value for the age of these filaments is 5×10^5 years based on a distance 6.9 for the nebula and an expansion velocity of 55 km s^{-1} (Lozinskaya 1973).

IX. DISCUSSION AND CONCLUSIONS

The model we have discussed in the previous section is valid when the star is single. If the star were double our observations would still indicate that the ejecting areas are roughly aligned and that matter is leaving the ejecting object in opposite directions. Smith states that WR stars associated with "ring" nebulae are single (Smith 1968*a*). But given the observational difficulties involved in this problem of WR stars the statement is open to question. If the WN5 star is double the mechanism and circumstances of ejection may be quite different from that which we have sketched above. Since a very high percentage of known WR stars are binaries (Smith 1968*d*) it is desirable to follow the star HD 56925 spectroscopically to check its duplicity.

We shall not attempt to explain all the details of the morphology and the velocity structure of NGC 2359. Our model may be too simple for such an attempt. Suffice it to stress that we have found a clear indication that the ejection from the parent star (or object, if double) has not been isotropic but essentially from nearly diametrically opposite regions, spots, on the ejecting object. Evidence for non-isotropic ejection is also shown by the twin H II regions NGC 6164-65 (Pişmiş 1974). What the origin and cause of these explosive phenomena may be is not clear at present. The symmetry of ejection and presumably the localized nature of the ejecting regions make it quite likely that magnetic forces are associated with the ejection mechanism.

If our interpretation of the ring structure is correct we should expect to observe "ring" structures in other WR stars (or Of stars) in all possible orientations. NGC 6164-65 if seen along the axis of rotation, or close to it, would probably appear each with its "blobs" delineating a ring. It will be worthwhile to examine all nebulae associated with WR or Of stars to see whether a sequence due to varying orientation can be detected; unfortunately however the number of these objects is not sufficiently large for a reliable statistical treatment.

Finally we like to suggest that the Wolf-Rayet phenomenon which presumably is a later phase of the ejection which gave origin to the surrounding nebulae, may as well be due to the emanation of gas from essentially two or more symmetrically placed ed spots suggested in our model. It is stated (Underhill 1969) that the shapes of lines formed in the expanding atmosphere "of a WR star can be explained most simply by a uniformly expanding sphere". However it seems quite possible that expulsion of matter from a WR star at present, out of regions located symmetrically with respect to the center of the object, may present line profiles not distinguishable from that produced by spherical expansion. If this is the case, the observed velocities of expansion will depend on the orientation of the ejecting areas with respect to the line of sight. Thus in any given type or subtype of a WR star all values for the expansion velocity would be encountered. In fact estimated expansion velocities show considerable range; moreover there does not seem to be any significant correlation of the expansion velocity with the WR class, judging from the values listed by Underhill (1969). Therefore it may well be that the different expansion velocities reflect the effect of orientation of the ejecting regions of the object. In the light of these ideas it should be interesting to attempt an interpretation of the WR spectra.

We wish to thank Dr. W. A. Hiltner for his kind advice and help in the adaptation of the Varo image tube to our focal reducer. Facilities offered to one of us (P. P.) at the NASA, JSC are greatly appreciated. We also acknowledge the assistance of M. Moreno and A. Quintero at the telescope.

REFERENCES

Avedisova, V. S. 1972, *Soviet Astr.*, **15**, 708.
Courtès, G. 1960, *Ann. d'Astrophys.*, **23**, 115.
Crampton, D. 1971, *M.N.R.A.S.*, **153**, 303.
Georgelin, Y. P., and Georgelin, Y. M. 1970, *Astron. & Astrophys.*, **6**, 349.
Johnson, H. M., and Hogg, D. E. 1965, *Ap. J.*, **142**, 1033.
Lozinskaya, T. A. 1973, *Soviet Astr.*, **17**, 317.
Minn, Y. K., and Greenberg, J. M. 1973, *Astron. & Astrophys.*, **24**, 393.
Pikel'ner, S. B., and Shcheglov, P. V. 1969, *Soviet Astr.*, **12**, 757.
Pişmiş, P. 1974, *Rev. Mex. Astron. Astrof.*, **1**, 45.
Pişmiş, P., and Rosado, M. 1974, *Rev. Mex. Astron. Astrof.*, **1**, 121.
Pişmiş, P., and Moreno, M. A. 1976, *Rev. Mex. Astron. Astrof.*, **1**, 373.
Smith, L. F. 1968*a*, *M.N.R.A.S.*, **138**, 109.
Smith, L. F. 1968*b*, *M.N.R.A.S.*, **140**, 409.
Smith, L. F. 1968*c*, *M.N.R.A.S.*, **141**, 317.
Smith, L. F. 1968*d*, *Proceedings of the Symposium "Wolf-Rayet Stars"*, eds. K. B. Gebbie and R. N. Thomas (Boulder: Joint Institute for Lab. Astrophysics), p. 21.
Smith, L. F. 1973, *Wolf-Rayet and High Temperature Stars*, eds. M.K.V. Bappu and J. Sahade (Dordrecht: D. Reidel), p. 15.
Underhill, A. B. 1969, *Astrophys. Space Sci.*, **3**, 109.