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INTERNAL MOTIONS IN H II REGIONS. II THE RADIAL VELOCITY FIELD OF IC 443*

PARIS PIŞMIŞ AND MARGARITA ROSADO

Instituto de Astronomía
Universidad Nacional Autónoma de México
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RESUMEN

Se presentan las velocidades radiales obtenidas en casi 170 puntos de la nebulosa IC 443 usando dos interferogramas Fabry-Pérot en la línea de emisión Hα. La velocidad promedio obtenida para este objeto, remanente de una supernova, es de -3 km seg^{-1} y su velocidad de expansión es de 60 km seg^{-1}. La discusión de algunos detalles específicos indican que existen movimientos relativos de masa en el conjunto de filamentos que forman la cáscara de la remanente de supernova. En el extremo norte de la remanente se ha detectado el alejamiento del observador de dos filamentos. A lo largo de otro filamento hay una bifurcación, en donde la diferencia de la velocidad radial, de las dos ramas, llega hasta a 76 km seg^{-1}. Se sugiere que un campo magnético en la cáscara del remanente pueda explicar las velocidades relativas observadas.

ABSTRACT

The radial velocities determined from the Hα emission line on two Fabry-Pérot interferograms at nearly 170 points in the supernova remnant IC 443 have been presented. The mean velocity of the SNR is -3 km s^{-1}, while the velocity of expansion is around 60 km s^{-1}. The discussion of some specific features indicates that there are appreciable relative mass motions within the assembly of filaments over the supernova shell. In the northern edge the recession from the observer of two filaments is detected. Along another of the features there is a marked bifurcation, the difference in radial velocity of the two branches reaching up to 76 km s^{-1}. It is suggested that a magnetic field along the supernova shell may account for the observed relative motions.

Key words: SUPERNOVA REMNANT — INTERFEROMETRY — RADIAL VELOCITIES.

I. INTRODUCTION

The galactic nebula IC 443 is at present believed to be the remnant of a supernova. It has a very striking filamentary structure, resembling somewhat the Cygnus Loop. Several investigations on this object both in the optical and in the radio region have been made in the past decade. It is generally accepted that the assembly of the filaments (SNR), of which the outer boundary is distinctly circular, is expanding (van den Bergh *et al.* 1973).

Courtès was the first to point out that IC 443 has large internal motions, their dispersion amounting to ± 40 km s^{-1} (Courtès 1960). Lozinskaya, also applying the Fabry-Pérot technique, confirmed the large dispersion of velocities over IC 443 and showed that the SNR is expanding at a rate of 65 ± 7 km s^{-1} while the thermal and turbulent motions combined amount to 50 ± 10 km s^{-1} (Lozinskaya 1969). Although Lozinskaya mentions the existence of large relative motion of individual masses of gas, her data have not permitted a quantitative estimate of these mass motions.

The brightness and polarization structure, of IC 443 at λ2.8 cm, was investigated by Kundu and Velusamy (1971). The overall 2.8 cm map is found to be similar to that obtained previously at 6-cm wavelength (Kundu and Velusamy 1969). The 2.8 cm features are observed to coincide with the optical features. The polarization, both in degree

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and in position angle, is found to vary over the region. There is, however, some indication that the magnetic lines of force are oriented in the general direction of the filaments.

The distance of the SNR is not uniquely known. Lozinskaya gives a value of 600 pc while Dickel's estimate based on 21 cm measurements suggests a distance of not less than 2.2 kpc (Dickel 1973).

II. THE OBSERVATIONS

We have carried out Fabry-Pérot interferometry on IC 443 with a focal reducer at the Cassegrain focus of the 1-meter reflector of the National University of Mexico, installed at Tonantzintla. The interferograms were calibrated with a hydrogen lamp. Out of the four interferograms obtained two proved to be of excellent quality; these are used in the present work. Table 1 gives the details of the observational material.

The region covered by our observations is indicated in Figure 1 (Plate 8) which is a copy of a Palomar Schmidt plate taken by S. van den Bergh and kindly lent us for reproduction in this paper.

The measurements of the interferograms were performed on the Mann Comparator at the Applied Physics Division of the NASA Johnson Space Center. The data obtained on punched cards were processed at the Computer Center of the University of Mexico. The method of reduction is that given by G. Courtès (1960).

In Figure 2 and 3 we give the radial velocities of the Hα line determined from plates F 94 and F 99 respectively. The numbers indicate the radial velocity of the marked point. The complete velocity field, from the two interferograms combined, is depicted in Figure 4. The velocities are grouped, as in Paper I (Pişmiş 1974), into intervals; in this case, each interval covers 5 km s^{-1}. The enlargement of F 94, given in Figure 5 (Plate 9), may serve as a sample for the quality of the observational material on which the present investigation is based. We mention in passing that there exists a preponderance of positive velocities in the northern part of the SNR as compared with the north-eastern part as apparent in Figure 4.

To take full advantage of the information contained in an interferogram one should determine the intensity of a feature on the interferogram relative to the intensity of that feature on a direct plate. This procedure is particularly useful for a correct evaluation of the radial velocity field in regions, like IC 443, where the brightness distribution in Hα is inhomogeneous. However it is the dispersion of velocities that is mostly affected by the lack of homogeneity in the brightness. For our future work we plan to perform surface photometry on interferograms and direct plates alike, in order to obtain correction factors to be applied to the velocities and their dispersions.

That there exist large variations in the velocities is readily seen in the display of the data, particularly in Figure 4. At present we shall confine our discussion to only a few features of IC 443, features which may yield reliable results without photometry and which merit some attention at this stage. The data we have on the velocity dispersion based on widths of rings will await a later discussion.

TABLE 1

OBSERVATIONAL MATERIAL
FABRY-PEROT INTERFEROGRAMS OF IC 443

Plate Number	Basic Instrument	Etalon Interference Order	Filter (half width)	Eastman Kodak Emulsion	Length of Exposure	Date
F 94	100 cm reflector	p = 1060	Hα interference (10 Å)	098-01	180 min	January 22, 1974
F 99	100 cm reflector	p = 1060	Hα interference (10 Å)	098-01	180 min	February 17, 1974

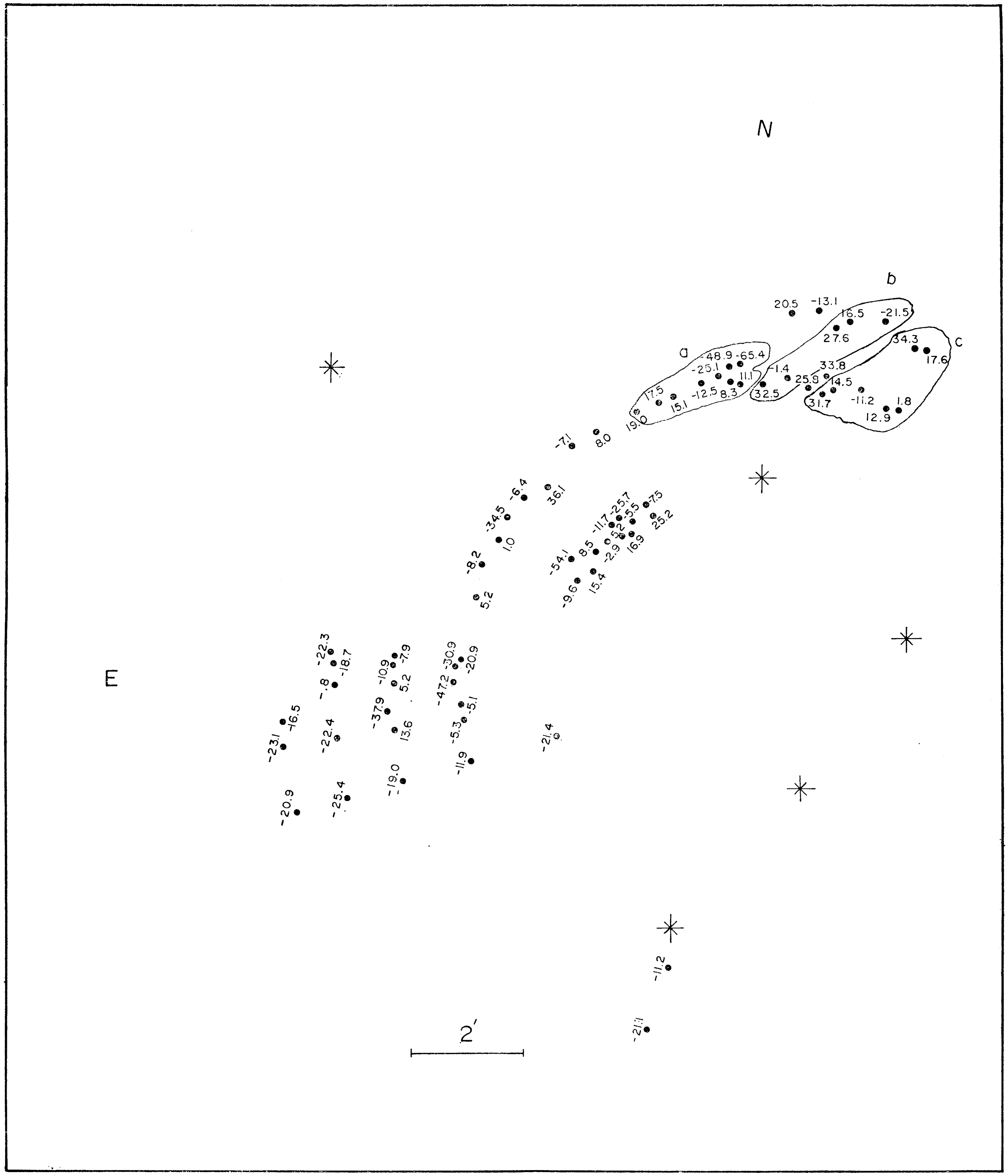

FIG. 2. Radial velocities in the region of IC 443 obtained from interferogram F 94 taken with the focal reducer attached to the 1-meter reflector of the National University of Mexico. The features in the closed curves designated by a, b and c are discussed in the text.

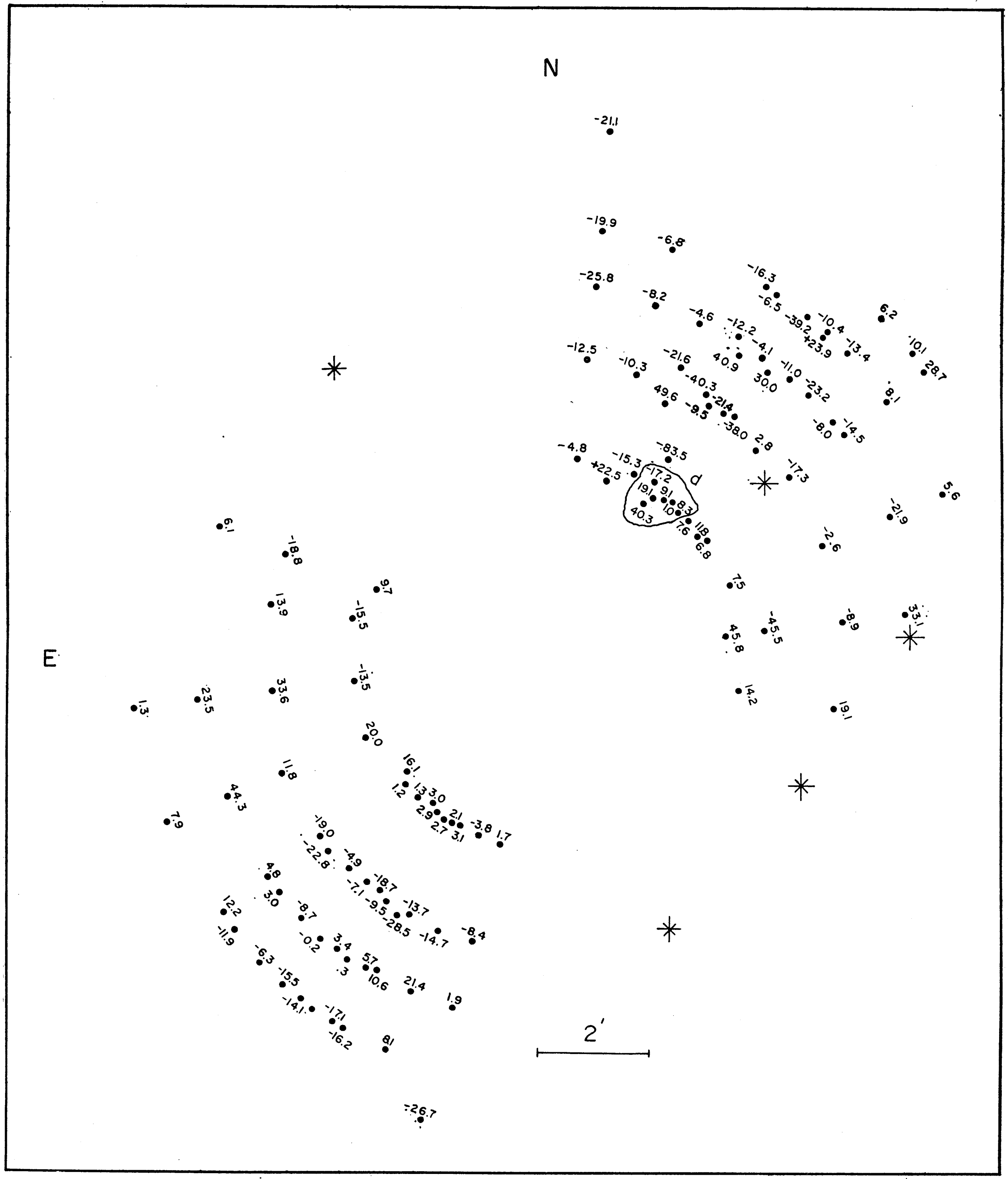

FIG. 3. Radial velocities in the region of IC 443 obtained from interferogram F 99 taken as in Figure 2. The feature in the closed curve, designated by d, is discussed in the text.

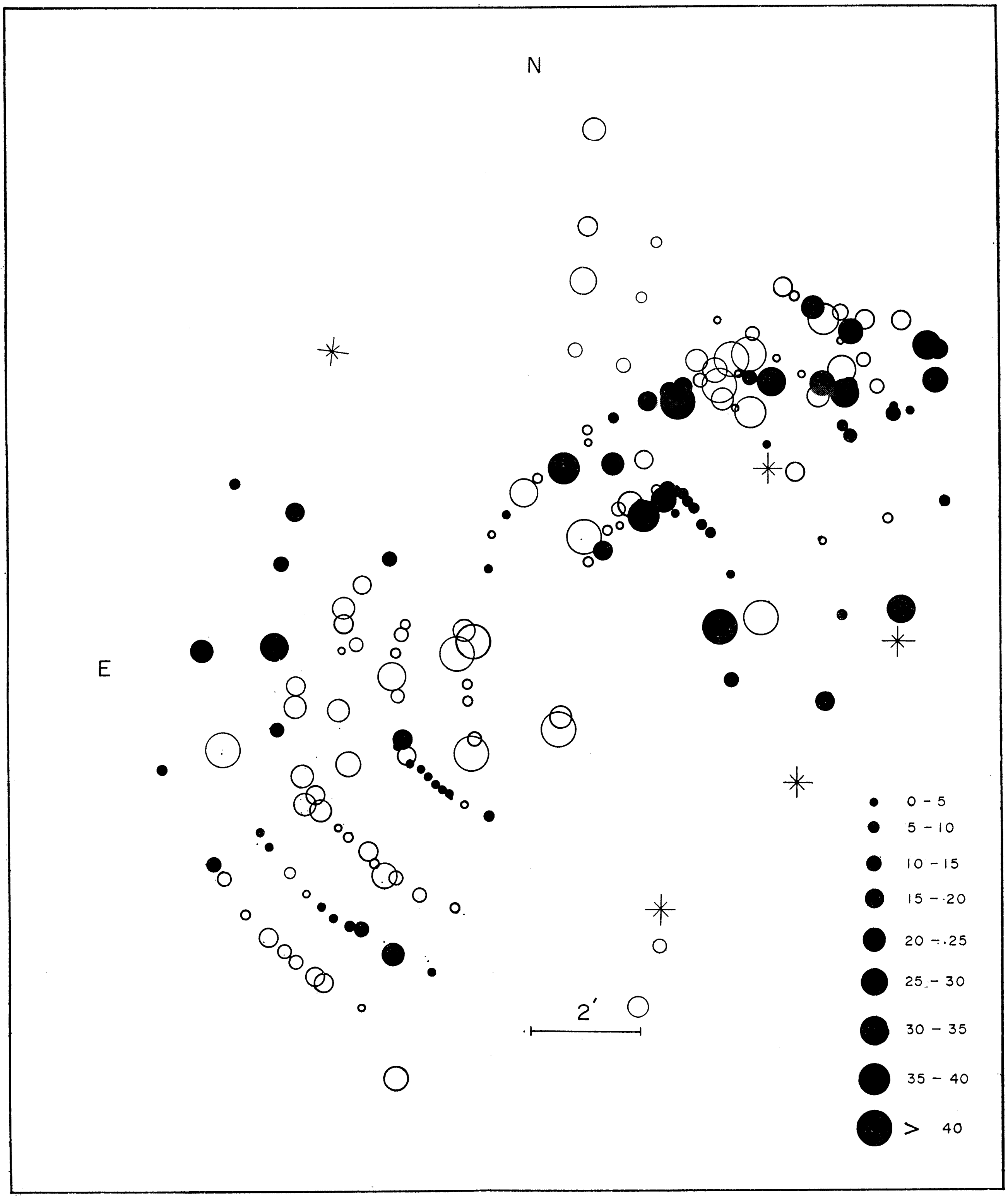

FIG. 4. Radial velocities from F 94 and F 99 plotted together. To the right of the plot is the scale for the velocity intervals. Open circles stand for negative and filled circles, for positive velocities.

III. ANALYSIS OF THE DATA

The average velocity of the SNR obtained from the measured points, 170 in all, is −3.0 km s^{-1}. With respect to the LSR, the velocity is −15.4 km s^{-1}. Lozinskaya gives +6 km s^{-1} for the LSR velocity of the object; the difference is quite large. We have not looked into the cause of this difference which may be due to a systematic difference in Lozinskaya's velocities and ours, or it might be due to the fact that the region covered by our data is smaller than that studied by Lozinskaya. The large velocity differences from point to point may also affect the average velocity. In any case the results obtained in this work are based on relative velocities in the SNR; systematic effects should not alter the conclusions reached in this paper.

We emphasize once again that the velocity distribution as seen in Figures 2, 3 and 4 is far from being smooth. Large deviations in radial motion exist within small areas. A few such areas which are associated with significant features appearing in the interferograms may be compared with the direct image of the SNR. The bewildering amount of detail appearing in Figure 1 makes it rather difficult to trace the gross structure of the SNR. To smear out the details an out of focus direct plate was obtained in Hα, with the focal reducer. An enlargement of this plate appears as Figure 6 (Plate 10). It is interesting to note that the gross features show a net-like structure. One set of the details follows nearly the outline of the SNR at its north-east border. The other set consisting of regularly spaced, parallel elements appears inclined towards the former set by about 75°.

The analysis of some specific features will preferably be done with the velocities obtained from each interferogram separately; in this manner one may avoid uncertainties which would otherwise creep into the combined plot of the velocities of a non-homogeneous field as is the case with IC 443.

In Figure 3 a region (d) is singled out where the velocities of its six points show a large scatter. The range covered is 57.5 km s^{-1}. If we assume that at this spot the far side of the SNR is projected on the near side, the velocity of expansion of the shell turns out to be 60 km s^{-1}, a value comparable to Lozinskaya's value of 65 km s^{-1}.

The northern tip of IC 443 is selected for an analysis of mass motions; the features marked a, b, and c in Figures 2 and 6 are well covered by the velocity measurements and are easily identifiable on the direct image. The average velocities of the three regions and the respective dispersion of velocities are given in Table 2.

The dispersion for feature a is most probably the effect of mass motions, as will be discussed below, while the dispersion of the velocities at b and c may be thermal; if so it would be compatible with a kinetic temperature of 20 000°K.

It is easily seen that the radial velocities in the third line of Table 2, velocities which refer to the

TABLE 2
VELOCITIES OF FEATURES a, b and c*

Feature	a	b	c
Mean velocity, km s^{-1}	− 9.0	10.7	10.4
Dispersion around mean; km s^{-1}	±31.2	±22.2	±21.9
Mean velocity referred to the SNR, km s^{-1}	− 6.0	13.7	13.4

* a, b and c are marked in Figures 2 and 6.

standard of rest of the supernova remnant, also refer to the plane tangent to the sky at IC 443. As our aim is to obtain the relative motions of a, b, and c on the supernova shell we need to estimate the line of sight component of the expansion velocity of the SNR at points a, b, and c and subtract them from the velocities given in the third line of Table 2. Adopting 65 km s^{-1} as the expansion velocity of the supernova shell, the line of sight components in question are found to be ±1.0, ±0.9 and ±5.1 km s^{-1} respectively; the ambiguity in the sign arises from our inability to ascertain whether the feature is at the near or the far side of the shell. Even if the corrections are positive for a, and negative for b and c, thus yielding the minimum values, there still remain appreciable radial velocities which are not explained by a simple expansion. It appears therefore that the features, the filaments, show mass motions relative to one another over the supernova shell.

Feature 1 deserves special attention. There is a clear bifurcation of the interference ring on which it happens to fall (see Figures 2 and 6). The relative radial velocity increases as the Y shaped feature opens up until the difference attains the value of 76 km s^{-1}. The outer branch is approaching us while the lower one is receding. There is no doubt about the physical reality of this feature and the associated difference in velocity. A plausible interpretation is that we are witnessing the relative motion of coherent masses, presumably filaments on the supernova shell.

IV. DISCUSSION

Let us accept, following Kundu and Velusamy's observations (Kundu and Velusamy 1971), that a magnetic field permeates the supernova shell at present and that the field lines are essentially along the shell, perhaps along the filaments. It is generally admitted that the bright shell of IC 443 is plowing into the interstellar matter. If so, the magnetic field, frozen into the matter, will be strengthened as a result of the compression of the shell. Part of the kinetic energy of expansion will be converted into thermal energy. The remaining kinetic energy while still capable of expanding the shell, may convert some of its energy into moving coherent masses along the lines of force where there is no resistance from the magnetic field.

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