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OBSERVATIONS OF THE EXPANSION OF THE OPTICAL REMNANT OF SN 1006 (LUPUS)

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ABSTRACT

Intercomparion of plates obtained in 1976 and 1981 shows that the optical remnant of the supernova of 1006 is expanding with $\mu=0''.39\pm0''.06$ (m.e.) yr^{-1}. Comparison with the value $\mu=0''.33$ yr^{-1} expected for a Sedov solution shows that the remnant is presently in the adiabatic phase of its evolution.

Subject heading: nebulae: supernova remnants

> A new star of unusual size appeared, glittering in aspect, and dazzling the eyes, causing alarm. It was seen likewise for three months in the inmost limits of the south, beyond all the constellations which are seen in the sky.
>
> *Annales Sangallenses Maiores* (1006)

I. INTRODUCTION

The supernova which appeared in May of 1006 was the brightest such object noted in recorded history. A detailed discussion of the ancient observations of this object is given by Stephenson, Clark, and Crawford (1977). These authors also published a high-resolution map of the radio source PKS 1459−41 which is located at the position of SN 1006. An X-ray map of this object obtained with the *Einstein* Observatory by Pye *et al.* (1981) shows a shell structure that closely resembles that seen at radio wavelengths. Both the X-ray and radio maps show the NE and SW parts of the shell to be brightest. The optical filaments discovered by van den Bergh (1976) lie along the NW part of the remnant where the radio and X-ray shells are faintest. In the present paper, the proper motion of optical filaments associated with this supernova remnant are studied by intercomparing the discovery plates obtained in 1976 with new CTIO 4 m plates taken in 1981.

II. OBSERVATIONS

Data for the available red and blue plates are listed in Table 1; the 1981 plates were obtained and processed in, as nearly as possible, the same manner as the 1976 ones. The structure of the filaments on the IIIa-J+GG 385 plates appears indistinguishable from that on the 098+RG 610 plates. The reason for this (Schweizer and Lasker 1978) is, no doubt, that the spectrum in both the red (Hα) and blue-green (Hβ, Hγ, Hδ) regions is dominated by Balmer emission. Also visual inspection suggests that no obvious structural changes in the filaments have occurred between 1976 and 1981. It should, however, be emphasized that the seeing was poorer during the 1981 observations than it was in 1976 so that subtle structural changes in the filaments might have escaped detection.

Due to the fact that the filaments are exceedingly faint, it was not possible to measure their motions with the coordinate measuring machines available to us. Scans approximately perpendicular to the direction of the filaments were therefore obtained with the PDS microdensitometer of the Dominion Astrophysical Observatory at the positions shown on Figure 1 (Plate 12). These scans were made through a 10 μm$\times$200 μm (corresponding to $0''.2\times3''.7$) measuring aperture with sampling taking place every 5 μm. In each scan at least one star was used as a reference benchmark. The proper motions were then determined by comparison of large-scale plots of the PDS data (smoothed by a 10 point boxcar) for plates P1980 and P5239. Differential motions among filament components sampled at a given position and/or intensity changes occurring within the nebulosity are very difficult to ascertain in these very faint filaments but may be contributing to some of the scatter in the 11 proper motion measurements summarized in Table 2. Were it possible to secure higher signal-to-noise ratio observations and/or when data over a larger time baseline become available, it may be possible to ascertain better if the scatter in the data of Table 2 is due to measurement errors, the effects of clumpiness in the interstellar medium, or other causes. The appearance of the Lupus SNR in 1976 and 1981 is compared in Figure 2 (Plate 13).

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TABLE 1

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Plate No.	Date (UT)	Emulsion	Filter	Exposure (min)	Seeing (arcsec)
P1980......	1976:04:26	IIIa-J	GG385	45	1.5[a]
P2014......	1976:04:28	098-04	RG610	60	1.6
P5239......	1981:04:01	IIIa-J	GG385	45	1.7[a]
P5257......	1981:04:02	IIIa-J	GG385	45	2.7
P5258......	1981:04:02	098-04	RG610	60	2.4

[a] FWHM determined from PDS scans.

TABLE 2

PROPER MOTION MEASUREMENTS

Position	μ (arcsec yr^{-1})	Position	μ (arcsec yr^{-1})
1...........	0.14	7.......	0.38
2...........	0.34	8.......	0.17
3...........	0.46[a]	9.......	0.55
4...........	0.42[b]	10.......	0.31
5...........	0.85[c]	11.......	0.40
6...........	0.28		

[a] Mean value for two components.

[b] SE component yields $\mu = 0''.24$ yr^{-1}.

[c] Alternative interpretation gives $\mu = 0''.38$ yr^{-1}.

III. DISCUSSION

From the X-ray map of Pye *et al.* (1981) it is seen that the optical filaments are situated at a mean distance of $\sim 810''$ from the geometrical center of the remnant of the Lupus supernova. The *mean* proper motion of expansion is therefore given by

$$\langle \mu \rangle = 810/(1978-1006) = 0''.83 \text{ yr}^{-1}. \tag{1}$$

A supernova remnant which has recently swept up a mass greater than that of the supernova shell will be in the adiabatic (Sedov 1959) phase of its evolution for which the radius R and age t are related by $R \propto t^{2/5}$, from which it follows that

$$\dot{R} = \mu = 0.4 \langle \mu \rangle. \tag{2}$$

Substitution of equation (1) into equation (2) yields an expected proper motion of $\mu = 0''.33$ yr^{-1} for the optical filaments in Lupus. This compares with an average observed value of $\mu = 0''.39 \pm 0''.06$ yr^{-1} that is obtained from the data in Table 2. As an alternative interpretation of the PDS scans at position 5, identifying the intensity maximum in the 1976 data with the weaker of the two maxima in the 1981 data yields $\mu = 0''.35 \pm 0''.04$ yr^{-1} which agrees even more closely with the value $\mu = 0''.33$ yr^{-1} predicted for a Sedov solution.

The X-ray map of the remnant of SN 1006 by Pye *et al.* shows that this object has an average radius of $\sim 15'$, from which it follows that its mass is

$$\mathfrak{M} \approx 12 n_z D^3 \mathfrak{M}_\odot, \tag{4}$$

in which n_z is the ambient density of hydrogen atoms cm^{-3} and D is the distance to the remnant in kpc. The value of the distance to SN 1006 is not well determined, but is usually assumed (cf. Stephenson, Clark, and Crawford 1977) to be ~ 1 kpc. Since the supernova remnant has $b = 14^\circ.5$, it then follows that it is located at a distance $z \sim 250$ pc from the galactic plane. Substituting $z = 250$ pc and $n_0 = 1$ hydrogen atom cm^{-3} into

$$n_z = n_0 \exp(-z/180) \tag{5}$$

(Kerr 1969; Lerche 1981) yields an expected value $n_z = 0.25$. Inserting this value into equation (4) yields $\mathfrak{M} \approx 3\, \mathfrak{M}_\odot$ for the mass of the supernova shell. This compares to a value $5 \lesssim \mathfrak{M}/\mathfrak{M}_\odot \lesssim 15$ which Pye *et al.* obtain from their X-ray observations. The latter value may be too high because of clumping since $\mathfrak{M} \propto n_e^2$. Alternatively, SN 1006 might well have occurred in a region with a slightly above average density. In any case, both a density model for the galactic gas and X-ray observations give masses that are well above the few tenths of a solar mass that is expected for the expanding shell of a supernova of Type I. The observation that SN 1006 is expanding adiabatically at $\mu \approx 0.4\langle\mu\rangle$ is therefore in agreement with expectation. In this respect SN 1006 resembles the remnant of Tycho's supernova (Kamper and van den Bergh 1978).

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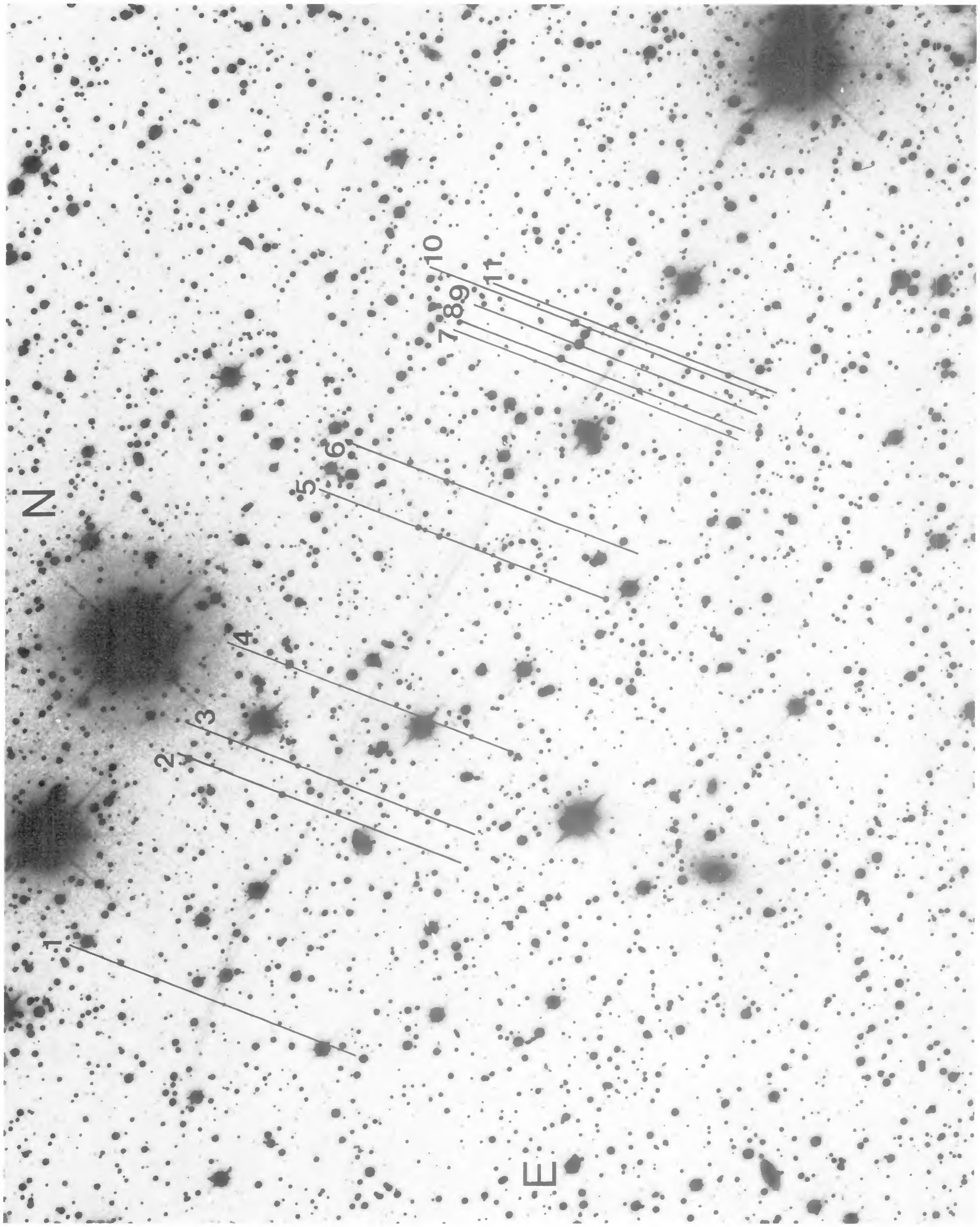

FIG. 1.—Positions at which proper motions of filaments were measured are marked on this print made from P1980, a IIIa-J+GG385 plate obtained with the CTIO 4 m telescope in 1976. The PDS slit was aligned at position 3 such that the stars nearest the filament (on each side of it) passed through the center of the slit.

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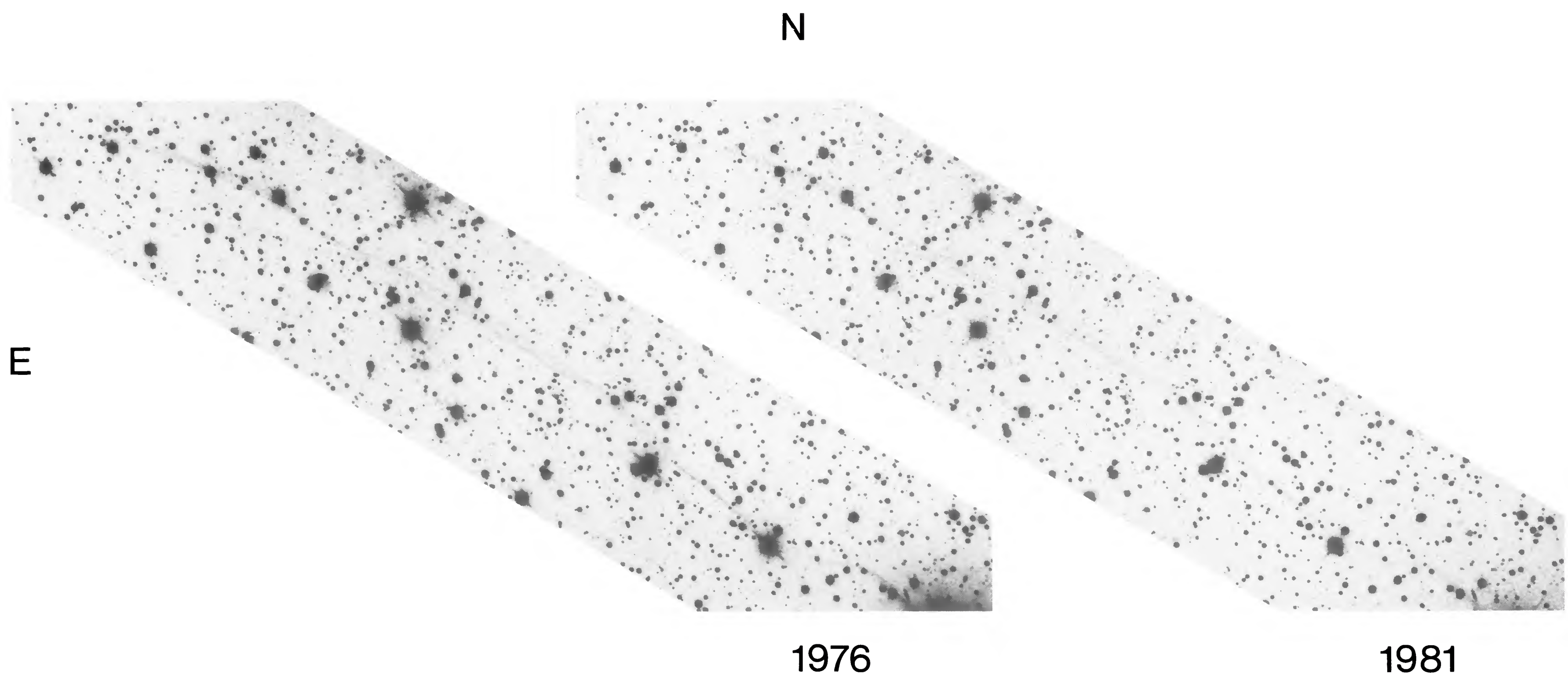

FIG. 2.—Montage comparing the appearance of the Lupus supernova remnant on IIIa-J+GG 385 plates obtained in 1976 and 1981. The motion of the filaments toward the northwest may be readily appreciated by inspection, say, near scan line 9 (cf. Fig. 1).

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