THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES No. 227, 26: 19–36

AN OPTICAL ATLAS OF GALACTIC SUPERNOVA REMNANTS

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Received 1973 January 29

ABSTRACT

In this *Atlas* we present photographs of 23 of the 24 known optical supernova remnants (the nebulosity associated with CTA 1 is too faint to be visible on a reproduction). A tentative classification scheme for optical supernova remnants is proposed.

Comparison of Baade's 1950 plate of Kepler's supernova with 200-inch (5-m) plates taken 20 years later shows that the fan-shaped optical remnant of this object is expanding with a proper motion $\sim 0''.03$ per year. Combining this result with Minkowski's radial-velocity observations and assuming a distance of 10 kpc yields an expansion velocity of ~ 1400 km sec^{-1} for the optical remnant of Kepler's supernova. This value is very similar to the expansion velocity of the Crab Nebula. Since Kepler's supernova is the prototype for supernovae of Type I, *the low expansion velocity of the Crab can no longer be used as an argument against the hypothesis that the Crab Nebula was produced by a supernova of Type I.*

A bright giant star embedded in a reflection nebula is used to derive a distance of 550 pc to IC 443. Combining this distance with the known expansion velocity and radius of this nebula yields an age $\ll$ 60,000 years. This value is inconsistent with the spindown time $P/(2\dot{P}) \sim 60{,}000$ years for the pulsar 0611+22 that is located $0^\circ.6$ from the center of IC 443. It follows that either (1) the distance to IC 443 is much greater than 550 pc or (2) the pulsar 0611+22 is not physically associated with IC 443.

It is pointed out that the optical object associated with the nonthermal source CTB 1 is morphologically very similar to the filamentary shell that surrounds the WN5 star HD 50896.

Subject heading: supernova remnants.

I. INTRODUCTION

During the past quarter century the study of supernovae and their remnants has occupied a central role in the development of astrophysics (Mayall 1962). It therefore seemed worthwhile to bring together in a single atlas photographs of all known optical supernova remnants in the Galaxy. The supernova remnants in the Large Magellanic Cloud have not been incorporated into this atlas because the great distance of these objects makes it difficult to compare their detailed structural characteristics with those of their galactic counterparts. It is hoped that this atlas will contribute in some small way to the study and classification of these enigmatic objects.

The catalogs of Milne (1970) and Downes (1971) constitute the basic working lists from which the present atlas was compiled. The positions of all but three of the sources listed by these authors could be studied on the *Palomar Sky Survey*, on special red

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plates taken with the 48-inch (126-cm) Schmidt, or on plates of a survey of the southern Milky Way that was recently conducted at the Cerro Tololo Observatory (van den Bergh and Racine 1973). Three radio sources (Milne Nos. 23, 38, and 40) fell outside the region of the sky covered by the Palomar and Cerro Tololo surveys. Minkowski (1965) reports that no nebulosity is visible near the position of Milne 40 = SN 1006. A total of 20 probable supernova remnants was found by inspecting the positions listed in Milne's catalog. (The remnants of Tycho's supernova of 1572 and of Kepler's supernova of 1604 would *not* have been found by inspection of the Schmidt plates.) In the anticenter direction ($90° \leq l < 270°$) almost three-quarters of the objects in Milne's catalog could be identified optically. On the other hand, only 13 percent of those in the direction of the galactic center could be optically identified. The low identification probability for remnants in the general direction of the galactic center is no doubt due to interstellar absorption. An unsuccessful search was made for a few objects, such as 3C 58, that are of special interest. Some nebulosity, that might warrant further study, was found near the positions of the sources Milne Nos. 18, 19, 36, 45, 79, 80, 82, and 89.

Inspection of all known supernova remnants shows that observers in the northern hemisphere occupy a highly privileged position. There are no remnants that can rival the beauty of the Crab Nebula, the Cygnus Loop, and S147 in the southern skies!

Descriptions of individual supernova remnants are given in § II. For more general discussions of observational data on supernova remnants the reader is referred to excellent reviews by Minkowski (1964, 1968), Shklovsky (1968), and Woltjer (1972).

II. DESCRIPTIONS OF INDIVIDUAL REMNANTS

The plate material on which these descriptions are based is listed in table 1. The observational data on individual remnants are summarized in table 2.

a) *CTA 1*

This source was discovered by Harris and Roberts (1960). A radio map by Caswell (1967) shows it to consist of an irregular shell with a spectral index $\alpha = -0.2 \pm 0.2$. On deep red ($\lambda\lambda$6400–6700) plates some exceedingly faint structureless nebulosity is visible. The fact that this faint nebulosity occurs near the brightest parts of the radio shell lends some support to the identification of these wisps with the supernova remnant. The nebulosity associated with CTA 1 is too faint to be visible on reproductions.

b) *Tycho's Supernova = B Cassiopeiae = 3C 10* (see pl. 1)

The optical remnant of B Cas consists of a number of exceedingly faint filaments that are strung out in an incomplete ring with a diameter of 8′. The remnant of Tycho's supernova was first detected on a red-sensitive plate taken by Baade with the 200-inch (5-m) telescope in 1949. Comparison with plates taken at later epochs (van den Bergh 1971*a*) shows that the faint filamentary shell of Tycho's supernova is currently expanding with a velocity $\sim 0\overset{''}{.}2$ per year. This velocity is slower than the expansion rate of $\sim 0\overset{''}{.}5$ per year that would be expected for uniform expansion. Intercomparison of plates taken during the last 23 years shows that individual filaments exhibit significant brightness changes on a time scale of ~ 10 years.

Early observations of Tycho's supernova of 1572 have been summarized by Baade (1945). From this discussion Baade finds that B Cas was a supernova of Type I which reached a maximum apparent brightness $V = -4.0 \pm 0.3$. The reddening suffered by this object is surprisingly well determined (van den Bergh 1970) from color estimates given by sixteenth century observers. From these observations $A_V = 1.6$ with a formal

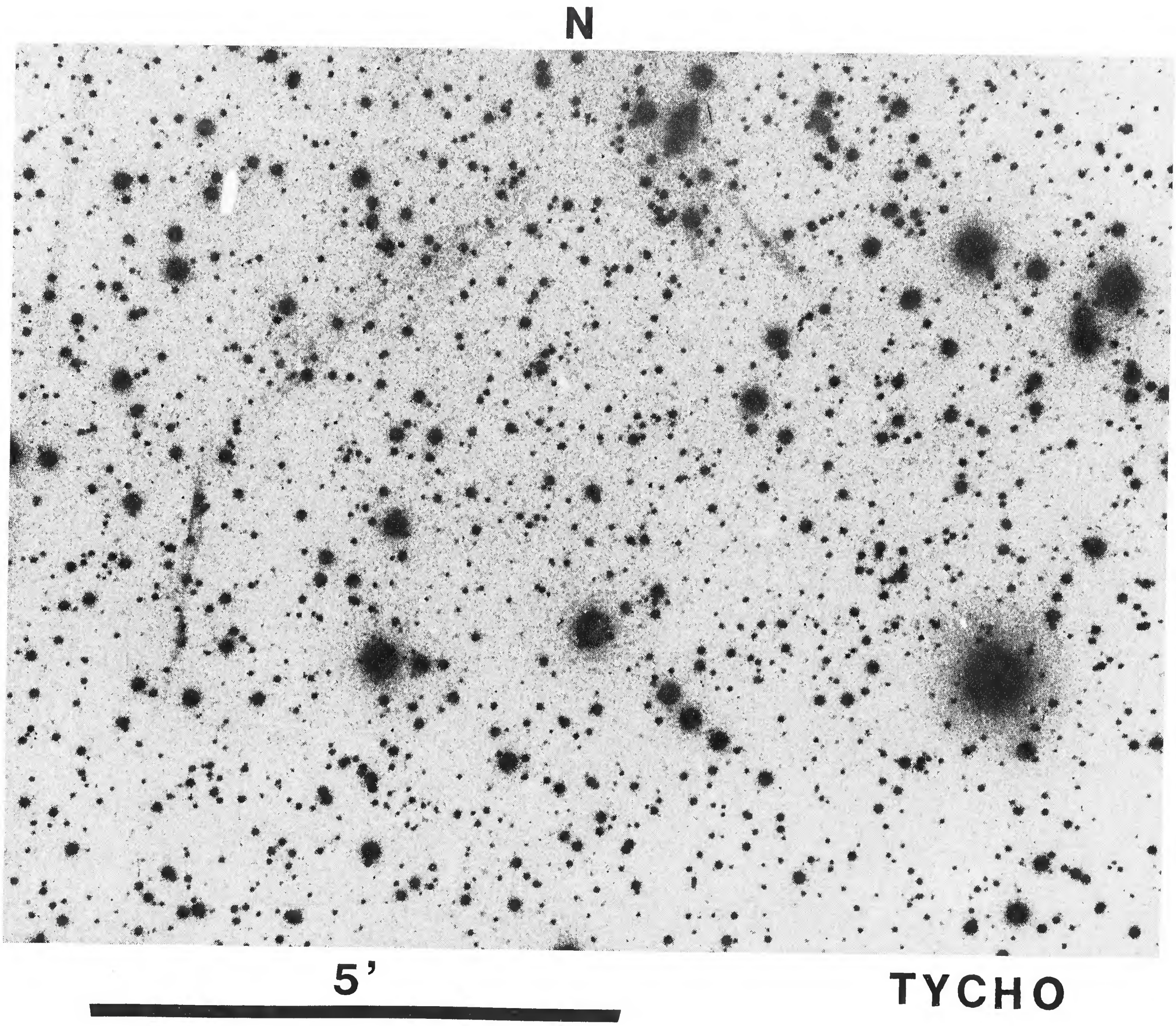

FIG. 1

VAN DEN BERGH *et al.* (*see* page 20)

TABLE 2

DESCRIPTION OF SUPERNOVA REMNANTS

No.	Name*	Galactic Coordinates l^{II}, b^{II}	α† (1950)	δ† (1950)	Source‡	Radio Size	Optical Size	Plate No.	Brief Description of Remnant
1 . . .	CTA 1	119°53, +9°77	00h04m18s	+72°04′5	R	90′	50′ × 90′	. . .	Very faint wisps of nebulosity
2 . . .	Tycho	120.09, +1.41	00 22 33	+63 51.8	R	8′	8′	1	Thin filaments forming an incomplete ring
3 . . .	HB 3	132.70, +1.30	02 14	+62 18	R	140′	. . .	2	Only one filament is visible
4 . . .	HB 9	160.39, +2.75	04 57	+46 36	R	130′ × 155′	90′ × 125′	3	Shell of diffuse filaments
5 . . .	OA 184	166.07, +4.40	05 15 38	+41 46	O	70′ × 90′	70′ × 80′	4	Shell of diffuse filaments
6 . . .	VRO 42.05.01	166.27, +2.53	05 23 21	+43 00	O	70′ × 75′	35′ × 40′	5	Sharp and diffuse filaments
7 . . .	S 147	180.33, −1.68	05 36 45	+27 44.5	R	175′	195′ × 200′	6	Shell of long delicate filaments
8 . . .	Crab	184.55, −5.78	05 31 31	+21 58.9		290″ × 420″	290″ × 420″	7	Amorphous spheroid, filaments embedded
9 . . .	IC 443	189.01, +3.02	06 14 06	+22 37.2	R	47′ × 54′	48′	8	Filamentary nebula, resembles Cygnus Loop
0 . . .	Monoceros	205.62, −0.10	06 35	+06 30	R	210′	180′ × 200′	9	Faint H II ring, some filaments
1 . . .	Puppis	260.40, −3.42	08 20 30	−42 50	R	45′ × 65′	50′ × 80′	10	Short bright arcs and flocculi
2 . . .	Vela	263.37, −3.01	08 32	−45 00	O	300′	270′	11	Long delicate filaments
3 . . .	MSH 10–53	284.17, −1.78	10 15 40	−58 40.5	R	33′ × 50′	1′ × 5′	12	A single filament
4 . . .	RCW 86	315.44, −2.33	14 39 08	−62 15	R	55′	8′ × 31′	13	Filamentary shell
5 . . .	RCW 89	320.36, −0.97	15 09 30	−58 46	O	8′:	450″ × 580″	14	Filamentary shell
6 . . .	RCW 103	332.43, −0.39	16 13 54	−50 55.8	R	7′	5′7 × 9′5	15	Filamentary shell
7 . . .	Kes 45	342.05, +0.13	16 50 11	−43 30.3	R	30′	. . . × 20′	16	Faint filaments in H II region
8 . . .	Kepler	004.52, +6.82	17 27 41	−21 26.6	R	3′	21″ × 64″	17	Fan of faint flocculi
9 . . .	W28	006.46, −0.09	17 57 36	−23 25	R	30′	30′	19	Filaments in an H II region
0 . . .	3C 400.2	053.62, −2.23	19 36 30	+17 08	R	20′	4′ × 6′	20	Faint, filaments?
1 . . .	DR 4	078.13, +1.81	20 20 38	+40 03.4	R	≲3′	2′ × 3′	21	*Not* filamentary
2 . . .	Cygnus	074.27, −8.49	20 49 30	+30 45	R	160′ × 240′	160′ × 210′	22	Shell of bright delicate filaments
3 . . .	Cas A	111.73, −2.13	23 21 10	+58 32.4	R	130′	130′	23ab	Moving knots and stationary flocculi
4 . . .	CTB 1	116.94, +0.18	23 56 45	+62 10	O	35′: × 45′:	32′	24	Faint filamentary ring

* Names refer to the following catalogs: CTA, Harris and Roberts 1960; CTB, Wilson and Bolton 1960; DR, Downes and Rinehart 1966; HB, Hanbury-Brown and Iazard 1953; HC, Holden and Caswell 1969; Kes, Kesteven 1968*a*; MSH, Mills, Slee, and Hill 1958, 1960, 1961; OA, Dixon, Meng, and Kraus 1965; RCW, Rodgers, ampbell, and Whiteoak 1960; S, Shajn and Gaze 1952; VRO, MacLeod *et al.* 1965; W, G. Westerhout 1958.

† Whenever possible, the position of the geometrical center of the source was used.

‡ R indicates a source position from radio observations; O, from optical data.

TABLE 1

DATA ON ATLAS PLATES

Plate No.	Remnant	Telescope	Plate + Filter	Exposure (minutes)	Date	Plate No.	Observer
....	CTA 1	Palomar 48-inch	103aE + OR1	100	1970 Sept.	PS 6106	van den Bergh
1............	Tycho	Palomar 200-inch	103aE + RG2	120	1970 Sept.	PH 5649vB	van den Bergh
2............	HB 3	Palomar 48-inch	103aE + OR1	60	1972 Aug.	PS 8204	van den Bergh
3............	HB 9	Palomar 48-inch	098–04 + OR1	67	1972 Aug.	PS 8201	van den Bergh
4............	OA 184	Palomar 48-inch	103aE + OR1	59	1972 Aug.	PS 8212	van den Bergh
5............	VRO	Palomar 48-inch	103aE + OR1	100	1970 Oct.	PS 6127	van den Bergh
6............	S147	Palomar 48-inch	103aE + OR1				Minkowski
7*...........	Crab	Palomar 200-inch	103aE + RG1	45	1952:		
8............	IC 443	Palomar 48-inch	103aE + RG1	60	1967 Jan.	PS 1571	van den Bergh
9*...........	Monoceros	Palomar 48-inch	103aE + red plexiglass	45	1953 Dec.	E 923	Sky Survey
10............	Puppis	Palomar 48-inch	103aE + OR1	60	1968 Dec.	PS 4433	van den Bergh
11............	Vela	Curtis Schmidt	103aO + UG2	120	1969 Feb.	3716	Bok
12............	MSH 10–53	Curtis Schmidt	098–02 + RG2	60	1970 Apr.	6306	DDO†
13............	RCW 86	Stromlo 74-inch					Westerlund
14............	RCW 89	Curtis Schmidt	098–02 + RG2	60	1970 Apr.	6398	Coutts†
15............	RCW 103	Curtis Schmidt	098–02 + RG2	60	1970 Apr.	6361	Coutts†
16............	Kes 45	Curtis Schmidt	098–02 + RG2	60	1970 Apr.	6297	Coutts†
17*...........	Kepler	Palomar 200-inch	103aE + RG2	98	1950 July	PH163B	Baade
19............	W28	Palomar 48-inch	098–04 + Hα†	120	1972 Aug.	PS8174	van den Bergh
20............	3C 400.2	Palomar 48-inch	098–04 + Hα†	120	1972 Aug.	PS8178	van den Bergh
21............	DR4	Palomar 48-inch	098–04 + Hα†	85	1972 Aug.	PS8161	van den Bergh
22............	Cygnus	Palomar 48-inch	098–04 + OR1	50	1972 Aug.	PS8188	van den Bergh
23a...........	Cas A	Palomar 200-inch	IIIaJ + GG7	120	1972 Sept.	PH6236vB	van den Bergh
23b...........	Cas A	Palomar 200-inch	103aF + RG2	120	1972 Sept.	PH6249vB	van den Bergh
24............	CTB 1	Palomar 48-inch	098–04 + Hα†	120	1972 Aug.	PS8197	van den Bergh

* Photograph courtesy Hale Observatory.

† Hα filter has a half-width of 120 Å and a peak transmission of 68% at 6615 ± 10 Å.

mean error of about 0.1 mag. Adopting this value for the absorption yields $V_0(\max) = -5.6 \pm 0.3$. The distance to Tycho's supernova is not well established. From 21-cm absorption-line observations Hughes, Thompson, and Colvin (1971) conclude that the distance to the remnant of Tycho's supernova is larger than 1.5 kpc.

Radio observations by Baldwin (1967) show that the radio remnant of Tycho's supernova (3C 10) is a beautifully symmetrical shell. Comparison of our figure 1 with Baldwin's radio map shows that the optical filaments are concentrated along the outer rim of the radio shell. This observation suggests that the delicate filaments that are seen in the light of Hα are probably thin emitting sheets seen edge-on. Both spectroscopic observations with the Cassegrain image tube of the 200-inch telescope and intermediate-band filter photography with the 48-inch Palomar Schmidt have so far failed to reveal λλ3727, 3729 of [O II] and λλ4959, 5007 of [O III]. Since the absorption between Tycho's supernova and us amounts to only 1.6 mag in visual light, the absence of [O II] and [O III] emission implies that these lines must be intrinsically weak. It is not yet clear how the rapid changes in the filaments, which imply short recombination times and hence high densities, are to be reconciled with the low emission measures of the filaments. A special search (van den Bergh, unpublished) has been made for a fossil Strömgren sphere surrounding the position of Tycho's supernova. No evidence for such an emission region was found on deep 48-inch Schmidt plates covering the wavelength intervals 6400–6700 Å (103aE + OR1) and 4600–5500 Å (IIIaJ + Wr4). This observation is significant (see Kafatos and Morrison 1971) because the interstellar density near Tycho's supernova is apparently large enough (van den Bergh 1971*a*) to have decelerated the expansion of this supernova.

A relatively bright star that is located almost exactly at the geometrical center of the supernova shell has a late-type spectrum. Attempts to obtain a spectrum of the faint bluish companion to this star have so far remained tantalizingly unsuccessful.

References to previous work on the remnant of Tycho's supernova may be found in Dickel (1969), Minkowski (1968), Shklovsky (1968), and Woltjer (1972). X-ray emission from B Cas was first detected by Friedman, Byram, and Chubb (1967). This is source 2U 0022+63 of the *Uhuru* catalog (Giacconi *et al.* 1972).

c) *HB 3 = CTA 2* (see pl. 2)

This radio source has been studied by Caswell (1967). HB 3 is roughly circular in outline and is brightest near its center. Study of this object is rendered difficult by the proximity of W3 (IC 1795). On our figure 2 the center of the radio source is located slightly above the SE corner of the print. The brightest filament shown in the plate is located along the western edge of the radio source. This filament might be associated with either the bright H II region IC 1795 or with HB 3. The low galactic latitude ($b = +2°$) of HB 3 suggests that the central part of the remnant might be hidden behind obscuring material. *It should be emphasized that the association of the filament shown in figure 2 with the supernova remnant HB 3 is very uncertain.*

d) *HB 9 = CTA 33* (see pl. 3)

This large shell source has been studied by Harris (1962), by Dickel and McKinley (1969), and by Willis (1972). The area of the radio shell is filled with diffuse emission nebulosity. Both the radio and the optical radiation are brightest in the southern part of this supernova remnant. The two brightest peaks in Willis's radio map (his sources A and B) have no optical counterparts. Possibly they are background sources. The bright sharp filament near the western edge of this supernova remnant is not a radio source. A few background galaxies are dimly visible through the supernova shell so that the absorption in the direction ($b = +3°$) of HB 9 cannot be very large.

1973ApJS...26...19V

PLATE 2

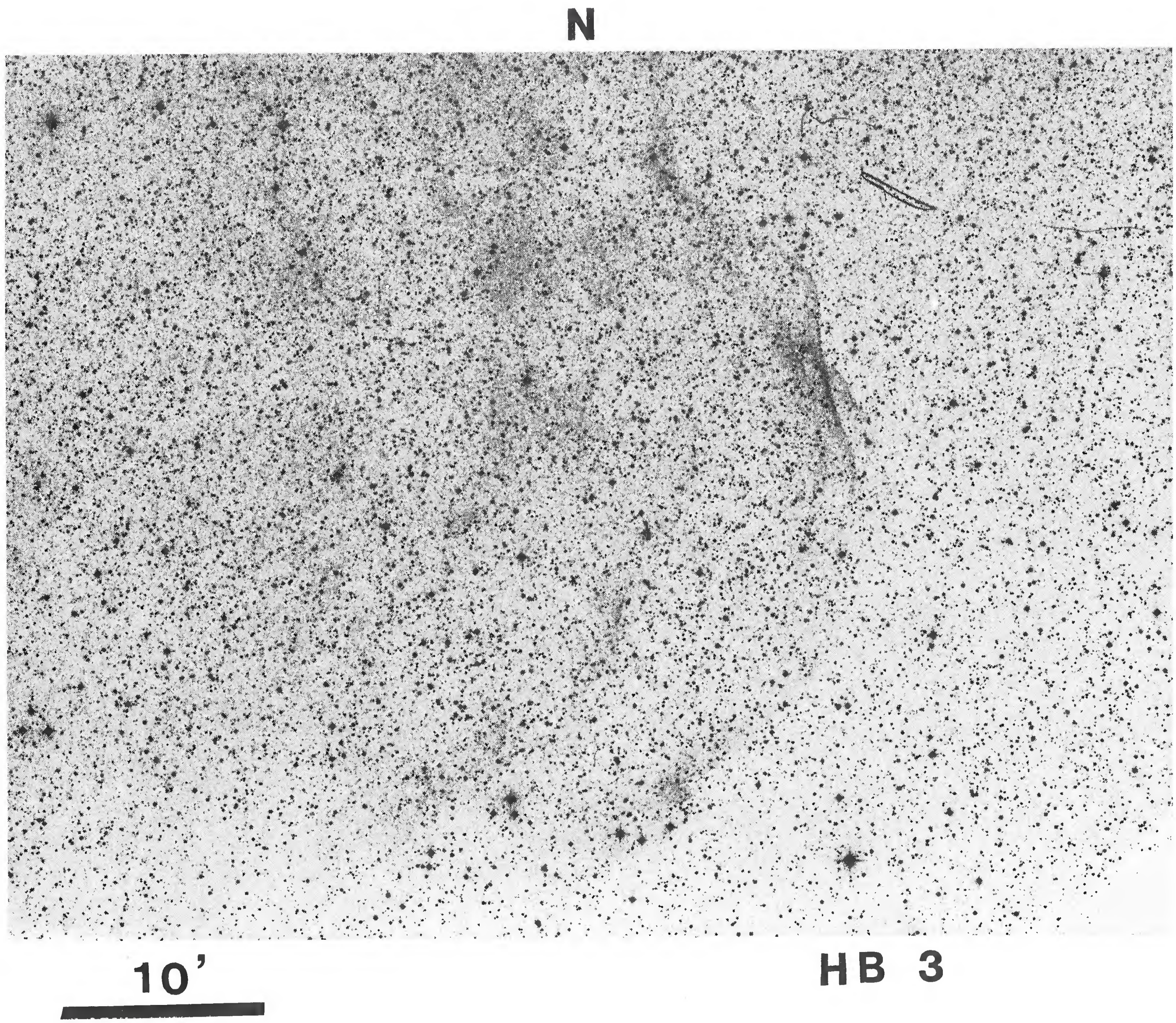

FIG. 2

VAN DEN BERGH *et al.* (*see* page 23)

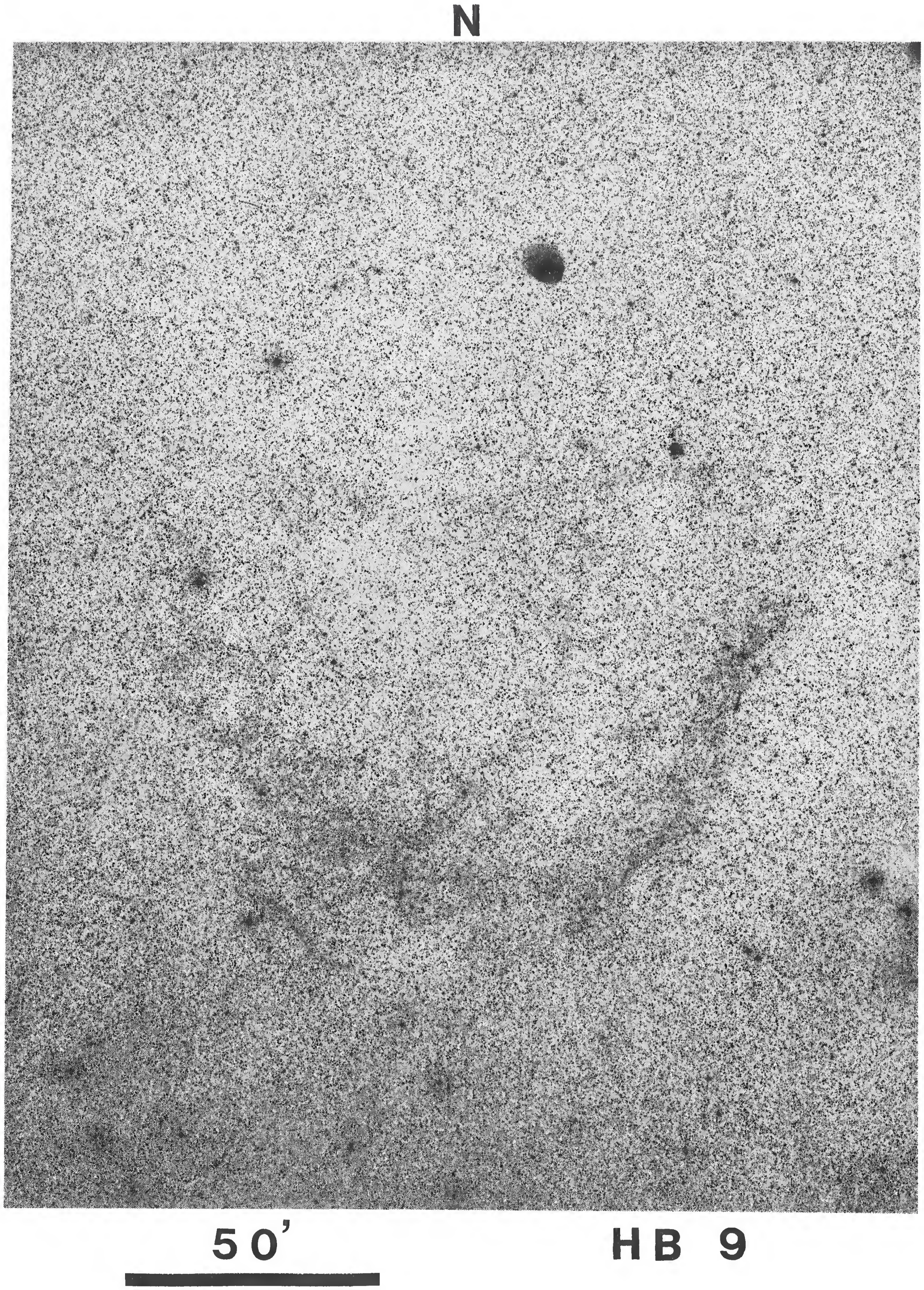

FIG. 3

VAN DEN BERGH *et al.* (*see* page 23)

e) *OA 184* (see pl. 4)

Both the radio isophotes of this object (Willis 1972) and its optical structure resemble that of HB 9. This supernova remnant consists of a complete shell of *diffuse* filaments. Both the radio and optical radiation is most intense along the NW rim of the shell. The position of this remnant has been taken from figure 4 because the optical nebulosity outlines the shell more clearly than do the radio isophotes.

f) *VRO 42.05.01* (see pl. 5)

The radio emission from this supernova remnant exhibits a complex structure (Dickel, McGuire, and Yang 1965; Willis 1972). The brightest optical filaments occupy a region of $20' \times 30'$ near the center of the radio source which has dimensions of $70' \times 75'$. This remnant contains both sharp and diffuse filaments. The long filament that runs north-south along the western edge of the remnant shows up prominently in Willis's radio map.

g) *S147* (see pl. 6)

Shajn 147 is perhaps the most beautiful supernova remnant in the sky. Long delicate filaments cover an area of $195' \times 200'$. Morphologically this object belongs to the same class as does the Vela XYZ remnant. A radio map by Dickel and McKinley (1969) shows the vestige of a radio shell. The radio brightness in this shell is seen to be slightly enhanced in those regions in which the brightest optical remnants are located.

A sharp bright filament in the NE quadrant of S147 resembles the bright sharp filament in HB 9. (The short horizontal streak in the northern part of the remnant [see our fig. 6] is a plate flaw.) A single filament in S147 has been studied by Parker (1964), who finds its temperature to be similar to that of the hotter filaments in IC 443 and the cooler filaments in the Cygnus Loop. Shajn 147 is located exactly in the direction of the galactic anticenter. Its distance is not known. Comparison with the Vela remnant suggests that S147 has a distance of less than 1 kpc.

h) *The Crab Nebula = Tau A = 3C144* (see pl. 7)

The Crab Nebula is the remnant of the supernova of 1054. The nebula consists of two distinct components: (1) a system of filaments that emits line radiation and (2) an amorphous component which emits synchrotron radiation. The radio radiation from the Crab comes from an elongated region, *which is brightest near its center* (A. S. Wilson 1972). The fact that the Crab is *not* a shell source is no doubt related to the fact that the energy radiated by the Crab is ultimately derived from the pulsar at the center of the nebula.

Woltjer (1958) has shown that in the Crab Nebula helium is overabundant relative to hydrogen by *at least* a factor of 2. More recently Davidson and Tucker (1970) have suggested that helium may be overabundant with respect to hydrogen by a factor of 6. Taken together with the work on Cas A by Peimbert and van den Bergh (1971), this constitutes the most direct evidence for nuclear transformations in supernovae.

Minkowski (1971) states that "the low expansion velocity of the Crab Nebula proves conclusively that the supernova of +1054 was neither a supernova of type I nor an average supernova of type II." This view may need to be modified because new optical observations of the optical remnant of Kepler's supernova, which are reported in this paper, show that it is expanding with a velocity similar to that of the Crab. Regarding Kepler's supernova Minkowski (1968) writes: "the light curve leaves no doubt that this supernova was of type I." On the basis of these results it is now no longer justified to conclude with certainty that the Crab Nebula was not produced by a supernova of Type I.

1973ApJS...26...19V

PLATE 4

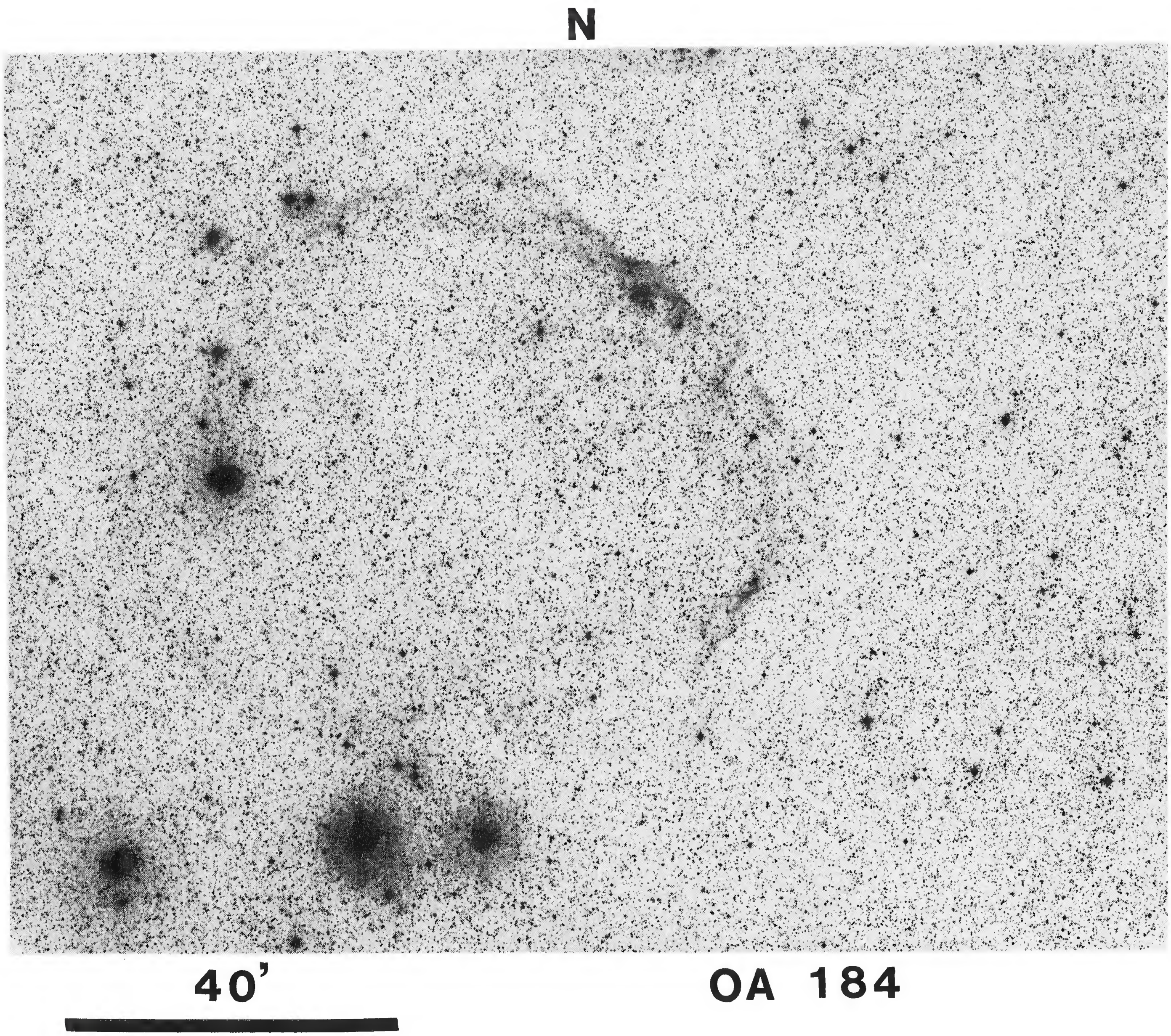

FIG. 4

VAN DEN BERGH *et al.* (*see* page 24)

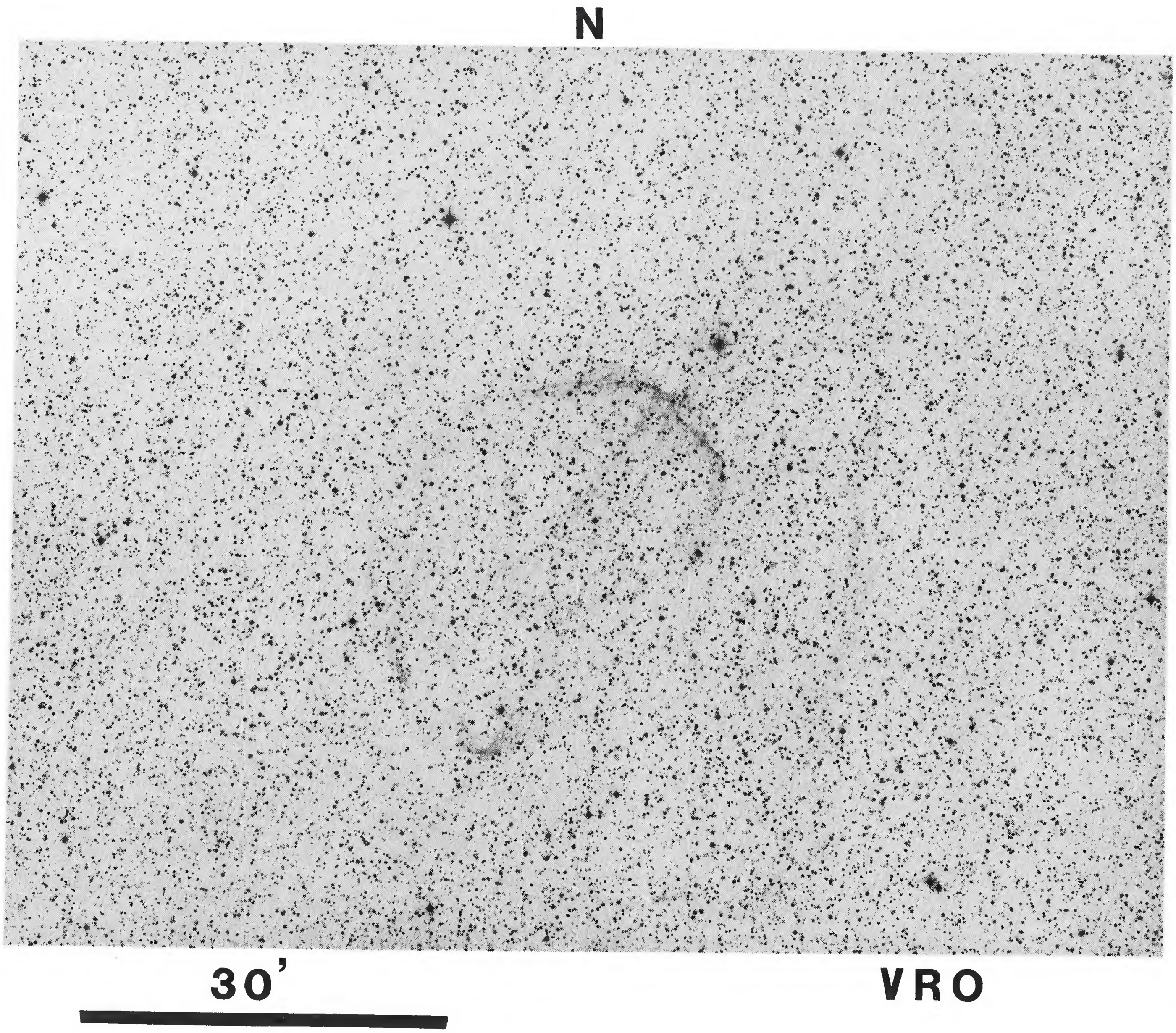

FIG. 5

VAN DEN BERGH *et al.* (*see* page 24)

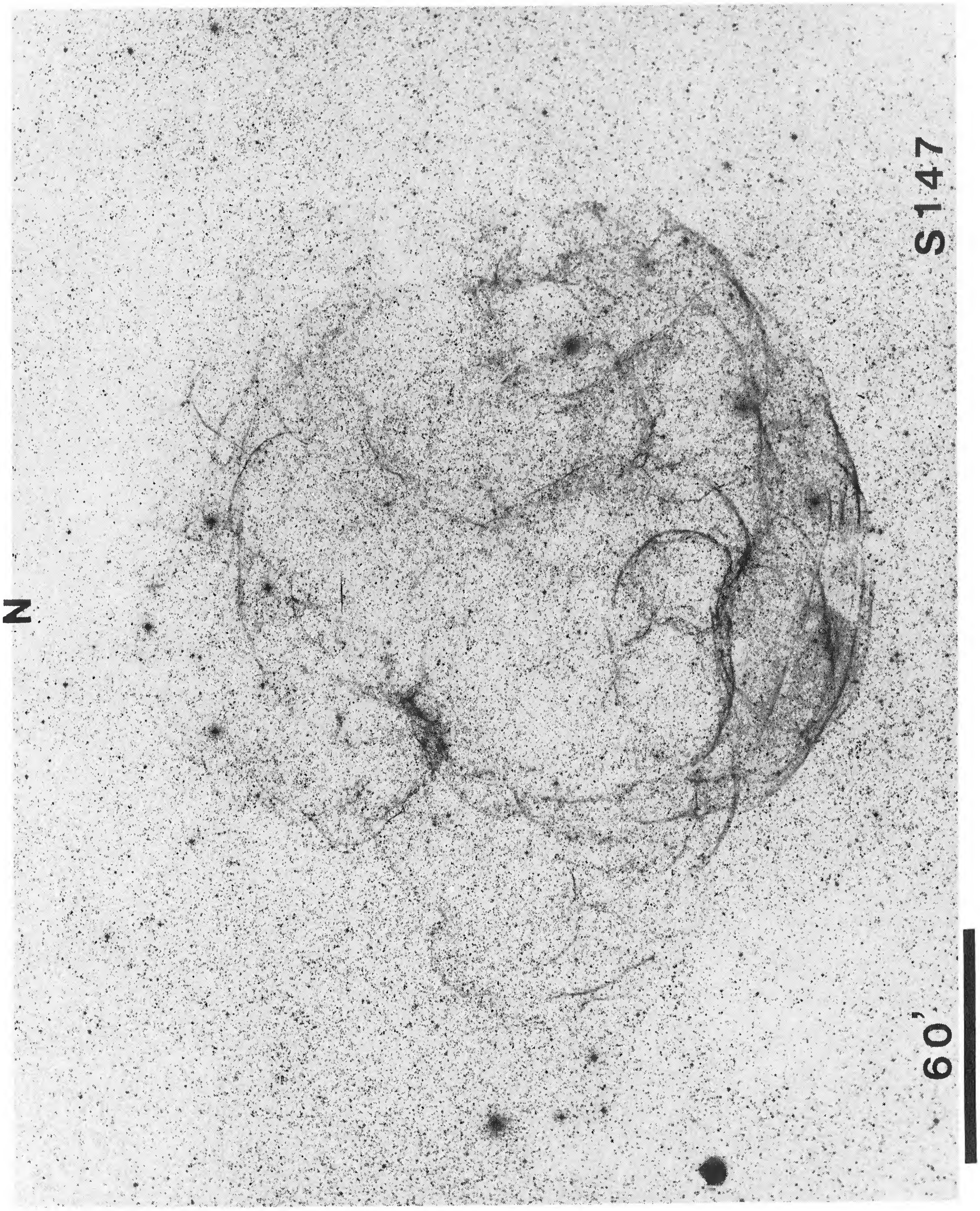

FIG. 6

VAN DEN BERGH *et al.* (*see* page 24)

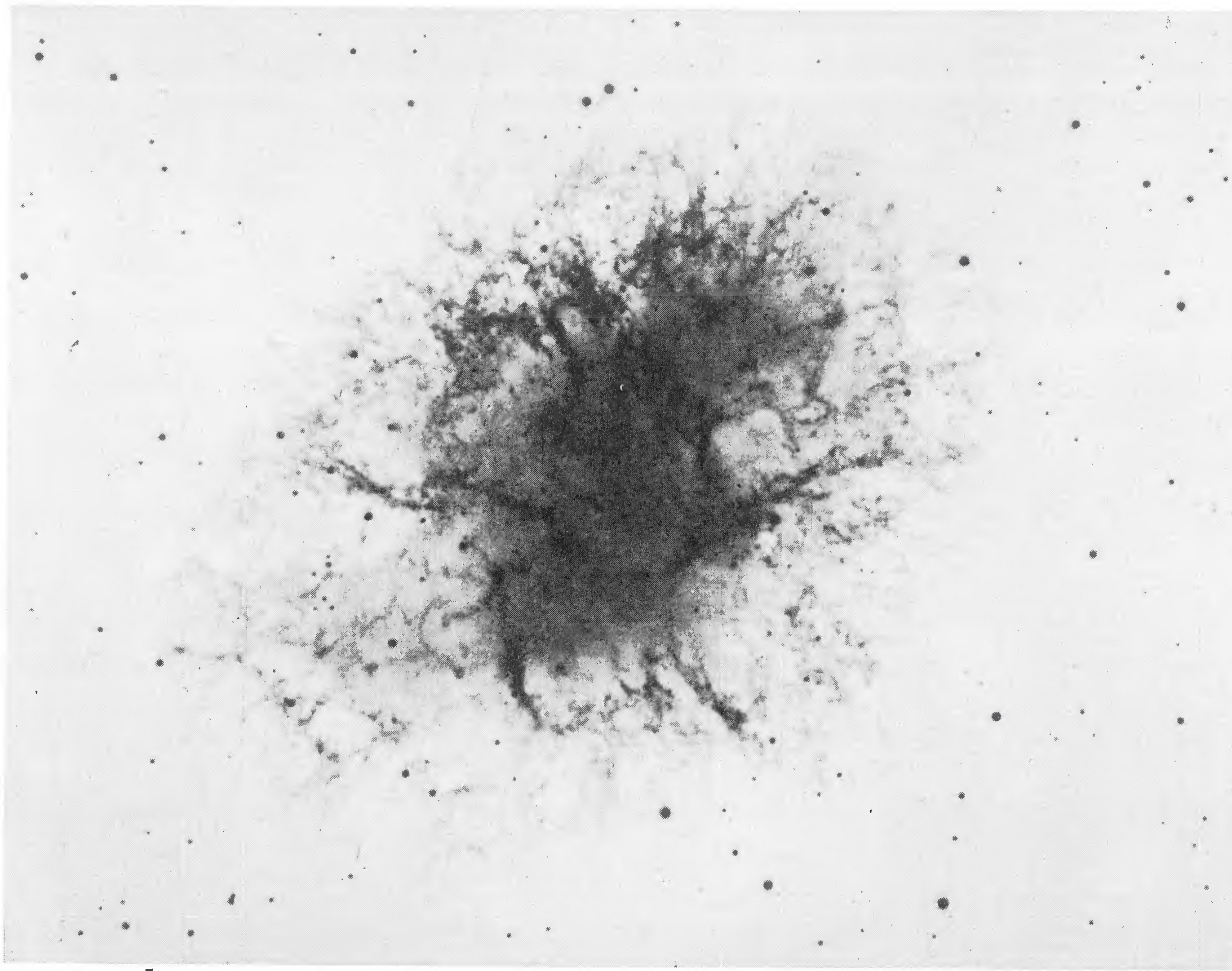

FIG. 7

VAN DEN BERGH *et al.* (*see* page 24)

References to the extensive literature on this remarkable object may be found in *IAU Symposium No. 46* (Davies and Smith 1971).

The Crab Nebula is the X-ray source 2U 0531+22, and contains at its center the pulsar NP 0531.

i) IC 443 = 3C 157 (see pl. 8)

IC 443 is a supernova remnant of the same morphological type as the Cygnus Loop. The temperature of the filaments in IC 443 is, however, lower than that of those in the Cygnus Loop (Parker 1964). The radial velocities of filaments in IC 443 have been studied by Lozinskaya and Esipov (1971) and by Lozinskaya (1969). These observations show that IC 443 is currently expanding with a velocity of 65 ± 7 km s^{-1}. From the present apparent radius of the supernova shell it then follows that the age of IC 443 is $\ll 1.1 \times 10^2 D$ years, in which D is the distance to IC 443 in parsecs.

IC 443 consists of crisp filaments that appear to be brightest in those regions in which the supernova shell is colliding with dense interstellar clouds. Good radio maps of this remnant have been published by Hogg (1964), Kundu and Velusamy (1968, 1969), Dickel (1971), Milne (1971), Hirabayashi and Takahashi (1972), Hill (1972), and Willis (1972). These maps show that radio emission is strongest from those regions in which the optical filaments are brightest.

It has generally been assumed that IC 443 is at the same distance as the I Geminorum (Gem OB1) association. The reality of this association is, however, in doubt (Hardie, Seyfert, and Gulledge 1960) because the early-type stars in this region appear to range quite uniformly in distance from 800 to 2500 pc. Gott, Gunn, and Ostriker (1970) assume that the Crab Nebula was formed by a runaway star from the (possibly non-existent) Gem OB1 association.

The NE part of the shell of IC 443 appears to be plowing into a cloud complex. Van den Bergh (1966) points out that the B9 II star HD 43836 may be illuminating part of this same cloud complex. *If* this assumption is correct, then HD 43836 may be used to estimate the distance of IC 443. From *UBV* photometry, MK classification, and the equivalent width of $H\gamma$ Racine (1968) obtains a distance modulus $(m - M)_0 = 8.7$ for this star. The corresponding distance to IC 443 is 550 pc, which is significantly smaller than the values usually quoted in the literature. From this distance, the angular size of the supernova shell, and the known expansion velocity of the remnant it follows that IC 443 must have an age $\ll$60,000 years. This value conflicts with the spindown time $P/(2\dot{P}) \approx$ 60,000 years that Davies, Lyne, and Seiradakis (1972) find for the pulsar that is situated at 0°6 from the center of IC 443. It follows that either (1) the distance to IC 443 is much greater than 550 pc or (2) the pulsar 0611+22 is not associated with IC 443.

The X-ray source 2U 0601+21 appears to be associated with this supernova remnant.

j) The Monoceros Ring = Downes 14 (see pl. 9)

This probable supernova remnant consists of a broken ring of filamentary nebulosity. Faint thin filaments are particularly well developed along the northern edge of this ring. The remainder of the ring has a more chaotic appearance. The Rosette Nebula is located at the SW rim of the ring, and NGC 2264 to the north of it (see fig. 12 of Morgan, Strömgren, and Johnson 1955, and Meaburn 1968).

From Fabry-Pérot interferograms Lozinskaya (1972) finds that the Monoceros ring is expanding with a velocity of 50 ± 10 km s^{-1}. Radio maps by Holden (1968) and by Milne and Hill (1969) show that the maximum of the radio emission lies along the *inner edge* of the optical filaments that outline the northern and northeastern parts of the ring.

1973ApJS...26...19V

PLATE 8

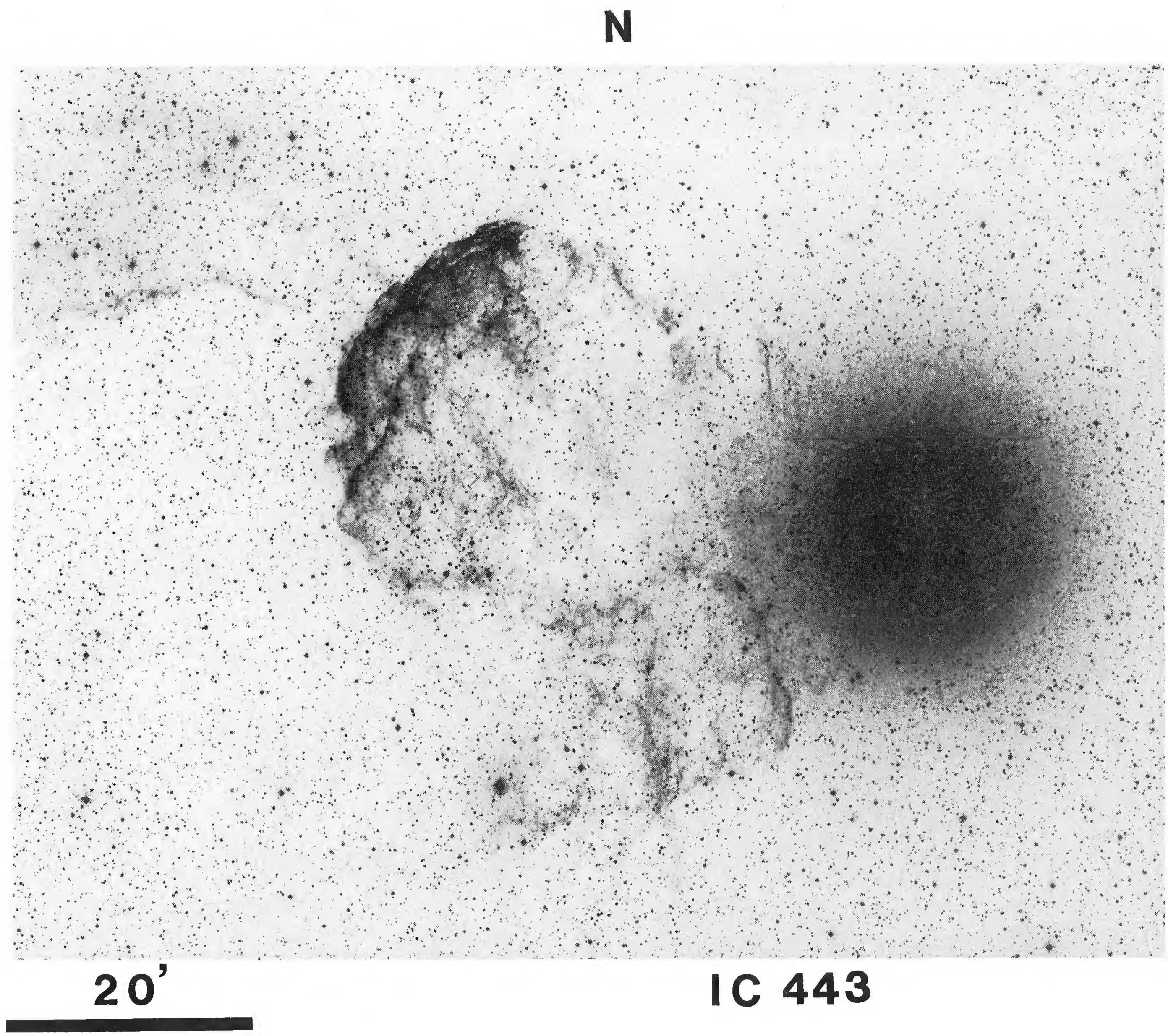

FIG. 8

VAN DEN BERGH *et al.* (*see* page 25)

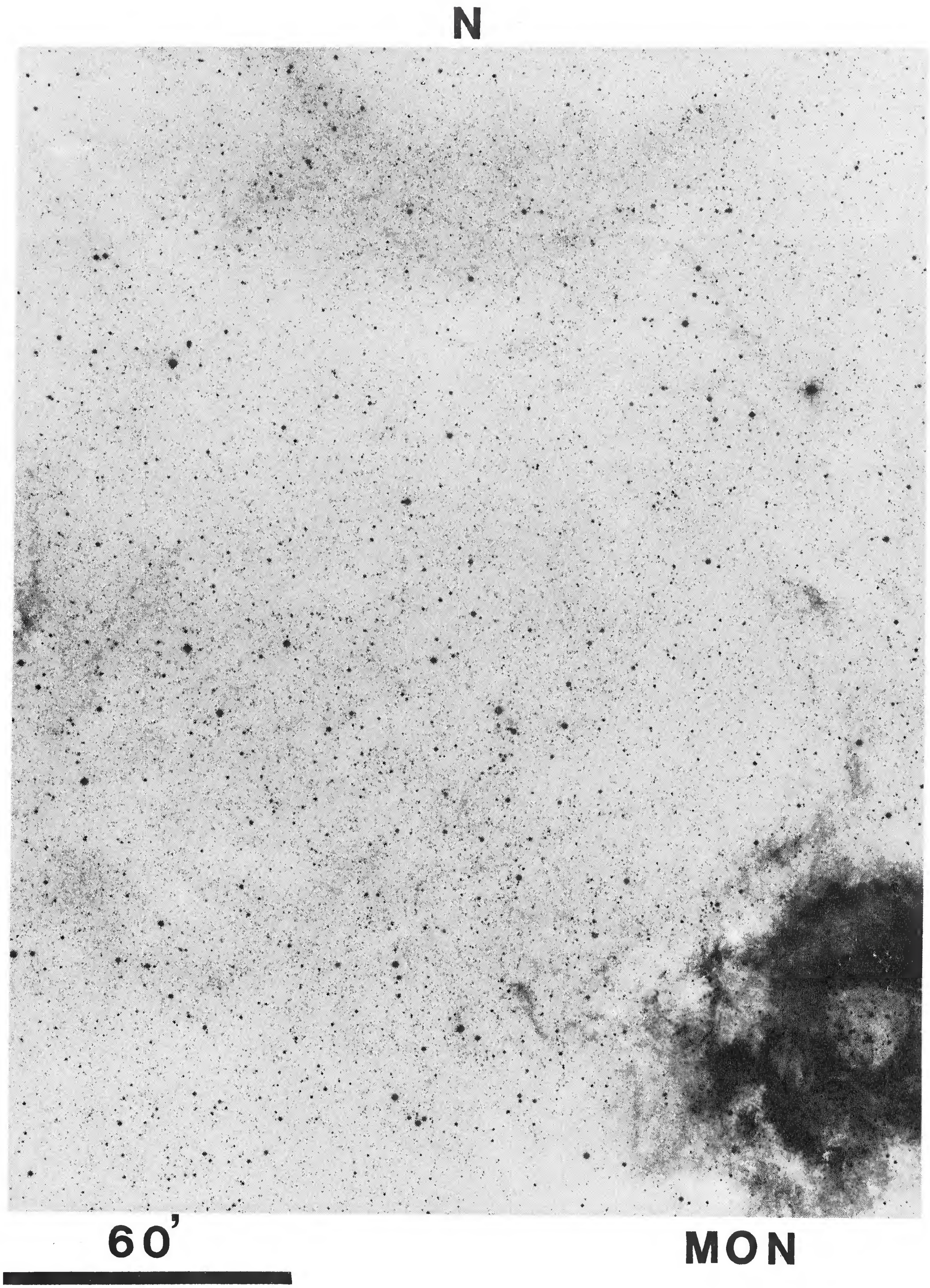

FIG. 9

VAN DEN BERGH *et al.* (*see* page 25)

k) *Puppis A* (see pl. 10)

The optical nebulosity associated with the radio source Pup A was first described by Baade and Minkowski (1954). On red plates the remnant is seen to consist of flocculi and short bright arcs of nebulosity. Intercomparison of the print published by Baade and Minkowski with a plate taken 20 years later shows no obvious structural changes. In this respect the Pup A nebulosity differs from the "stationary flocculi" associated with Cas A (van den Bergh 1971*c*). No other optically known supernova remnant exhibits flocculi and bright arcs quite like those observed in this object. Spectra by Minkowski show a velocity dispersion of 150–200 km s^{-1} within individual filaments. The positions of the northern and eastern intensity maxima on the radio maps by Kundu (1970), by Green (1971), and by Milne (1971) agree well with the positions of the brightest optical nebulosity. The western point source in Green's radio map does not correspond to any optical feature and may be due to an extragalactic background source. Perhaps the most unexpected result of a comparison of the radio and optical data on Pup A is that *the filamentary nebulosity located northwest of the center of this source lies well outside the radio shell.* Seward *et al.* (1971) have reported the discovery of X-rays from Pup A. This is source 2U 0821−42.

l) *Vela* (see fig. pl. 11)

The Vela supernova remnant consists of long delicate filaments similar to those in S147. According to Milne (1968*b*) these filaments are superposed on faint background emission. The region covered by the Vela filaments has a diameter of 270′ and is centered at $\alpha_{1950} = 8^h32^m$, $\delta_{1950} \simeq -45°$. The fact that this position is close to that of the pulsar 0833−45, for which $\alpha_{1950} = 08^h33^m.6$, $\delta_{1950} = -45°00'$ has led to the speculation that this pulsar is the stellar remnant of the supernova that produced the Vela filaments. If this is correct, then S147 might also be expected to contain a pulsar. The fact that none is observed *might* be accounted for if the view of the radiating cone from the pulsar in S147 does not intersect the Earth.

It has been suggested that the Gum Nebula is a "fossil Strömgren sphere" produced by the ionizing radiation emitted by the Vela supernova (Brandt *et al.* 1971). This hypothesis is discussed in more detail in Maran, Brandt, and Stecher (1971). Intercomparison of 48-inch Schmidt plates taken with an epoch difference of 3 years shows no evidence for expansion on a time scale shorter than $\sim 1 \times 10^4$ years (van den Bergh, unpublished). This is comparable to the spindown time $P/(2\dot{P}) = 1.1 \times 10^4$ years for the Vela pulsar. Radio observations of the Vela source are given by Milne (1968*a*) and by Davies and Gardner (1970). The source is roughly circular with its center near $\alpha_{1950} = 8^h39^m$, $\delta_{1950} = -44°20'$. It has a radius of $\sim 150'$. Superposed on this faint circular source is a stronger compact source (Vela X) that has a radius $\sim 75'$ and is centered at $\alpha_{1950} = 8^h34^m$, $\delta_{1950} = -45°30'$. The positions of both of these sources differ somewhat from that of the Vela pulsar (see table 3).

The optical filaments are distributed throughout the entire volume of the Vela source but are more frequent near the core source Vela X than they are near the outlying Vela Y and Vela Z components.

In summary, there does *not* appear to be a close correspondence between the positions of optical filaments and radio hot spots. In this respect the Vela source is similar to the young supernova remnant Cas A and differs from such old remnants as the Cygnus Loop and IC 443. The conclusion that the Vela nebulosity is a supernova remnant is strongly supported by the observation (Wallerstein and Silk 1971) of interstellar absorption lines with radial velocities of −86 and −172 km s^{-1} in two stars that are situated only 3° from the center of the radio source. Seward *et al.* (1971) report the discovery of a soft X-ray source that is possibly associated with the Vela supernova remnant. This is the source 2U 0832−45.

FIG. 10

VAN DEN BERGH *et al.* (*see* page 26)

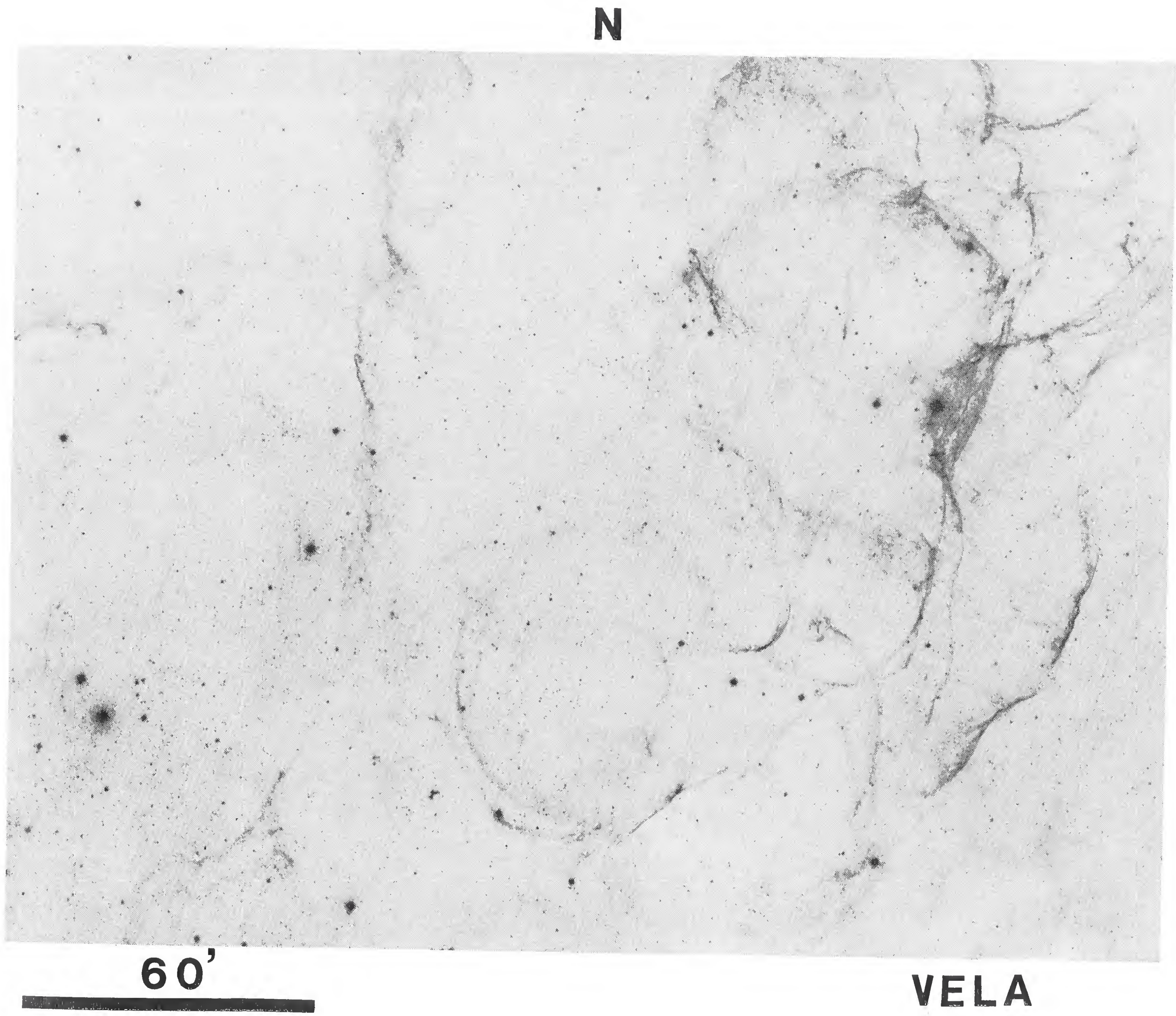

FIG. 11

VAN DEN BERGH *et al.* (*see* page 26)

TABLE 3

COMPARISON OF THE POSITION OF THE VELA PULSAR WITH THE POSITION OF THE VELA RADIO SOURCE

	α (1950)	δ (1950)
Center of symmetry of the radio source Vela XYZ......	8^h39^m	$-44°20'$
Radio center of Vela X........	8 34	−45 30
Vela pulsar	8 33.6	−45 00
Center of optical filaments	8 32:	−45:

m) *MSH 10−53* (see pl. 12)

A single isolated optical filament is visible in the northeastern part of the radio source (Milne 1972).

n) *RCW 86 = PKS 1439−62 = MSH 14−63* (see pl. 13)

Inspection of a Curtis Schmidt plate of RCW 86 shows it to consist of two parts: (1) a set of bright filaments bearing a superficial resemblance to the Cygnus Loop (see fig. 13) and (2) an elongated filament that resembles MSH 10−53. The bright Cygnus Loop-like filaments coincide with the brightest parts of the rim of the radio source (marked C on the photograph reproduced by Hill 1967). The elongated filament (marked A in Hill 1967) coincides with an area of enhanced emission on the northern edge of the RCW 86 shell. Polarization measurements in RCW 86 are reported by Milne (1972). A spectrum of RCW 86 by Westerlund and Mathewson (1966) shows strong λλ6717, 6731 of [S II]. This great strength of the ionized sulfur lines is characteristic of many supernova remnants. Westerlund (1969*a*) finds a concentration of early B stars at a distance of 2.5 kpc in the direction of this supernova. It has been suggested that RCW 86 was possibly produced by the supernova of +185.

o) *RCW 89 = Kesteven 23* (see pl. 14)

RCW 89 consists of delicate filamentary nebulosity that fills a region measuring roughly $8' \times 10'$. This supernova remnant appears to be located in a region of heavy obscuration. This may account for its low surface brightness. A radio map by Goss and Shaver (1970) suggests that the radio size of this object is comparable to its optical dimensions. The filamentary structure of the optical remnant rules out Downes's (1971) suggestion that this is a background galaxy.This source is *not* MSH 15−52.

p) *RCW 103 = Kes 33 = PKS 1613−50* (see pl. 15)

This supernova remnant consists of a bright filamentary shell. As in the case of the Cygnus Loop, the brightest parts of this shell are located at opposite sides of the source. According to Westerlund (1969*b*) two filaments in RCW 103 have radial velocities of −70 and +10 km s^{-1}, respectively. Line intensity ratios in RCW 103 are given by Westerlund and Mathewson (1966). The high intensity of [S II] λλ6717, 6731 strengthens the conclusion that RCW 103 is a supernova remnant.

A comparison of the optical and radio structure of this object (Kesteven 1968*b*) shows that the radio and optical sources have similar dimensions. The brightest radio emission appears to come from those portions of the shell that are brightest optically.

1973ApJS...26...19V

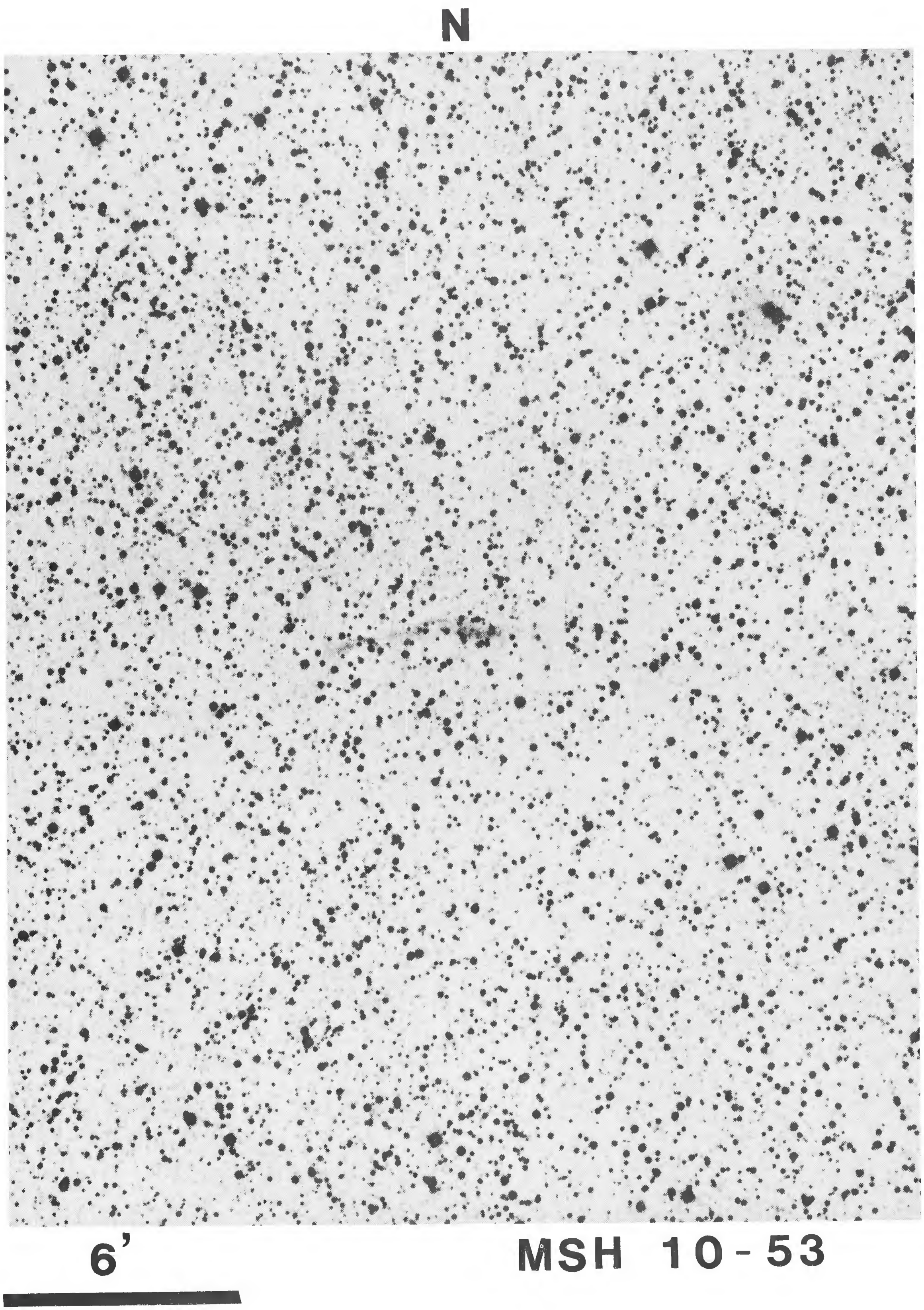

FIG. 12

VAN DEN BERGH *et al.* (*see* page 27)

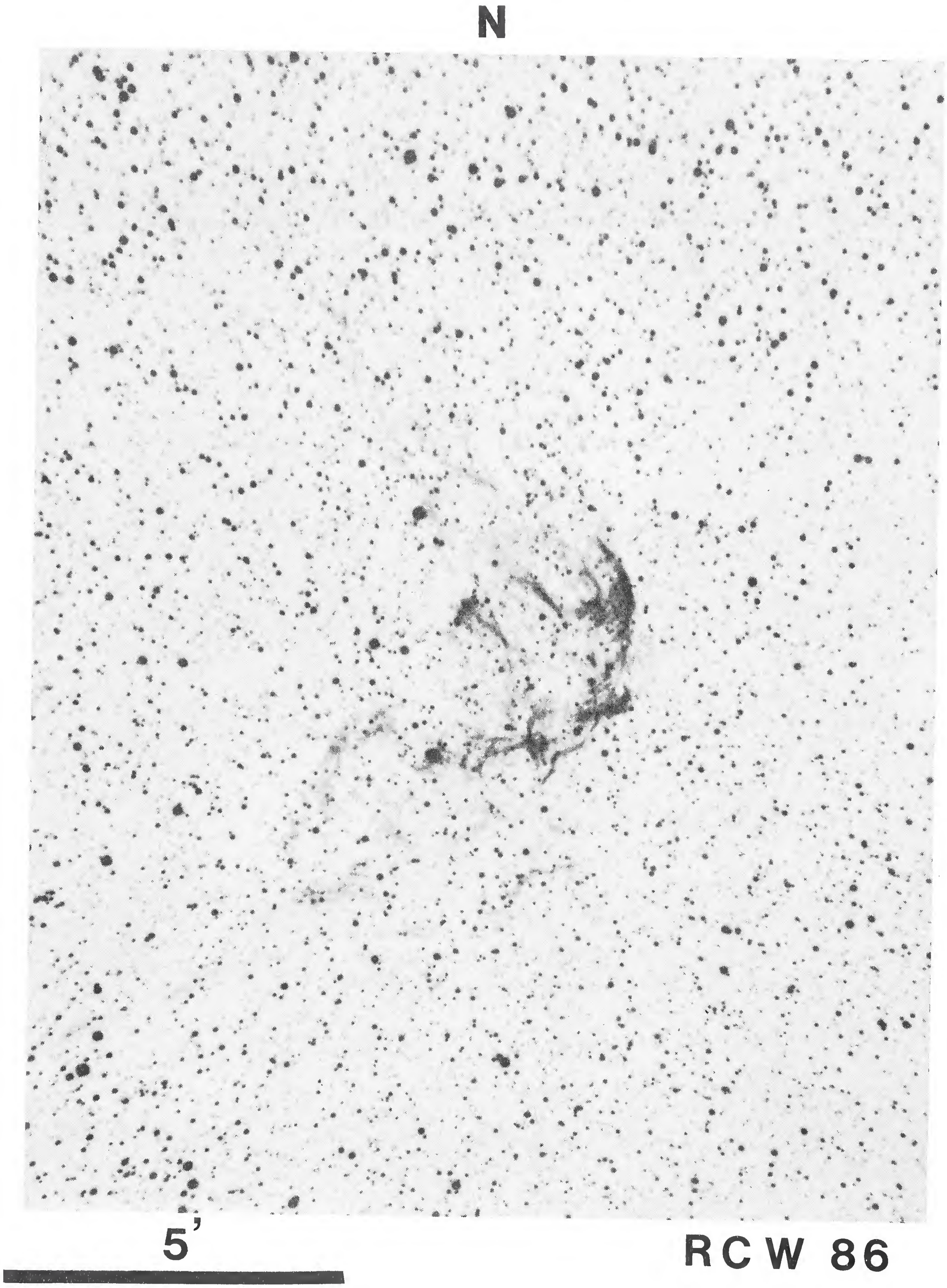

FIG. 13

VAN DEN BERGH *et al.* (*see* page 27)

1973ApJS...26...19V

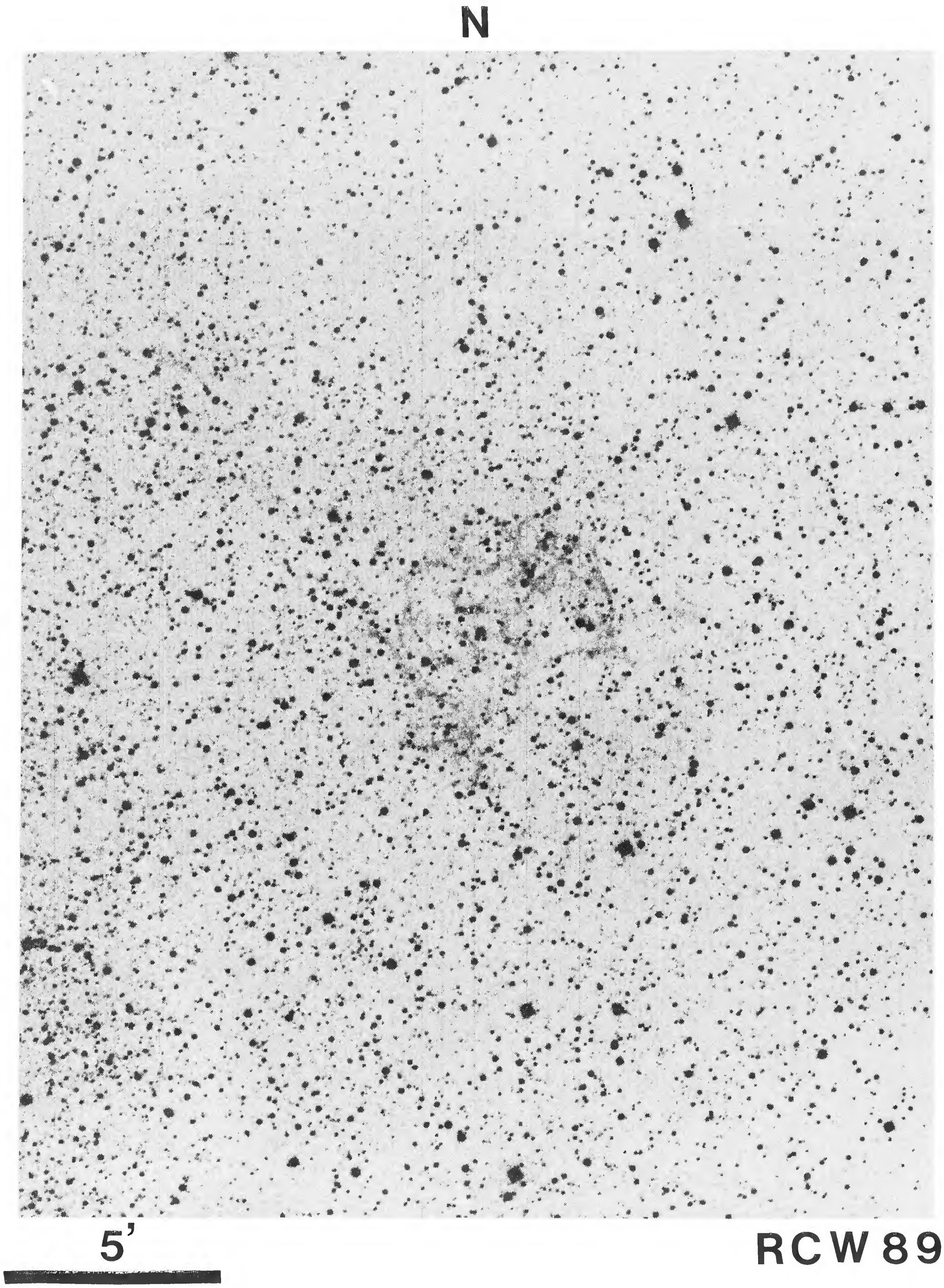

FIG. 14

VAN DEN BERGH *et al.* (*see* page 27)

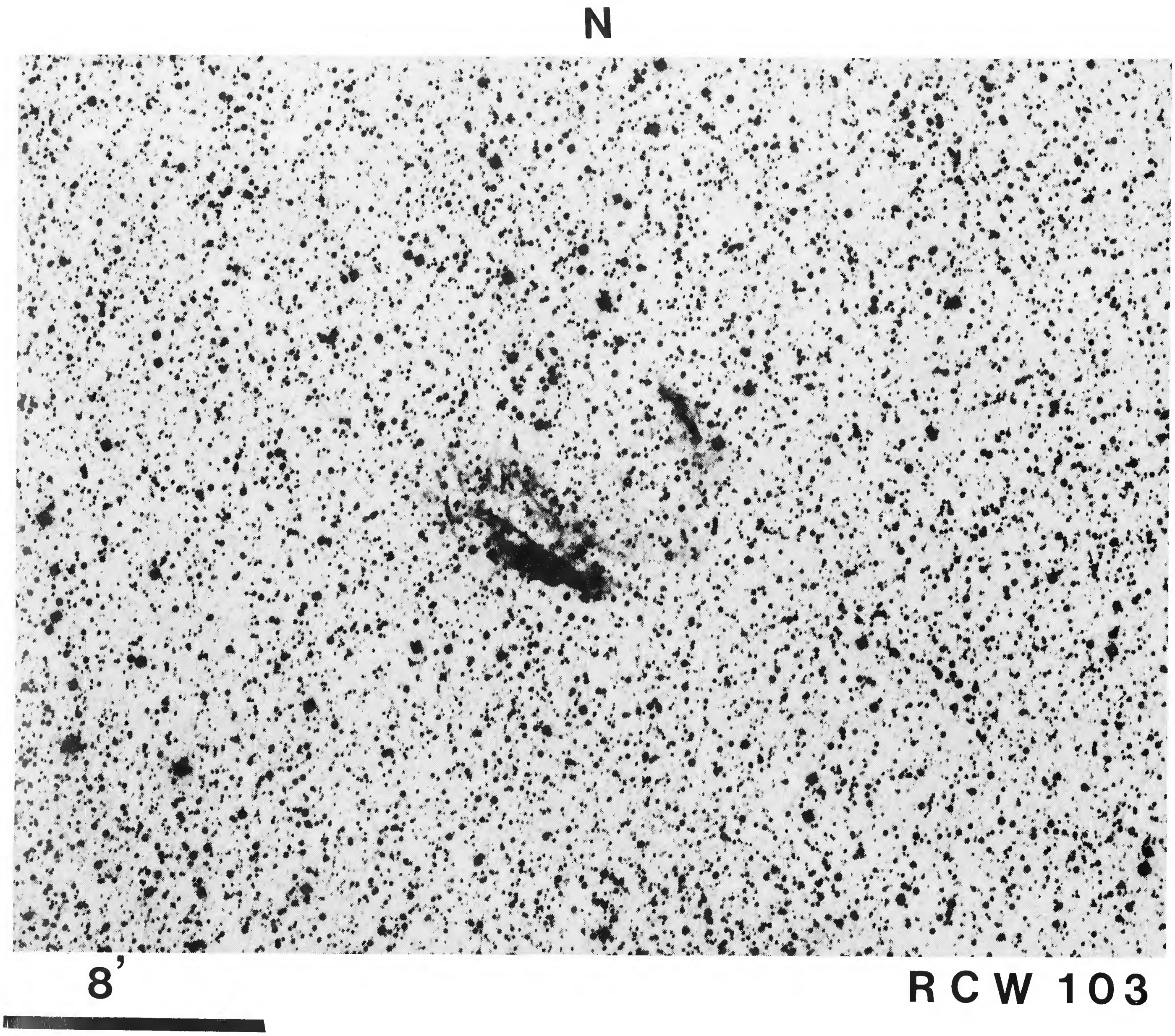

FIG. 15

VAN DEN BERGH *et al.* (*see* page 27)

q) *Kesteven 45 = MSH 16−48* (see pl. 16)

The area of this large radio source coincides with part of a faint extended H II region on which sharp-edged absorption features (fossil H II regions) are superposed. Two areas containing faint filaments, which are superposed on the background (?) H II region, are marked on figure 16. The identification of these filaments with the supernova remnant is uncertain.

r) *Kepler's Supernova = SN Ophiuchi 1604 = 3C 358* (see pl. 17)

Seventeenth century optical observations (Baade 1943) show that Kepler's star of 1604 was a supernova of Type I, which reached an apparent magnitude $V(\max) = -2.2$. The spectrum of the optical remnant of this object has been discussed by Minkowski (1943). Minkowski's spectra showed emission lines of [O III] λλ4959, 5007; of [O I] λ6300; of [N II] λλ6548, 6584; of [S II] λλ6717, 6731; and of Hα. According to Minkowski (1964) the reddening of Kepler's supernova was between 0.0 and 0.4 mag greater than that for Tycho's supernova for which $A_V = 1.6$ (van den Bergh 1970), so that $1.6 < A_V < 2.8$. The corresponding value of $V_0(\max) = -4.4 \pm 0.6$. According to Kowal (1973*a*, *b*) $M_V(\max) = -18.3 + 5 \log (H/100)$ for supernovae of Type I. (The dispersion in the luminosities of Type I supernovae $\simeq 0.6$ mag.) With $M_V(\max) = -18.3 \pm 0.6$ ($H = 100$ km s^{-1} Mpc^{-1}) this yields $(m - M)_0 = 13.9 \pm 0.8$, corresponding to a distance of 6.0 kpc and $Z = 0.7$ kpc. (For $H = 50$ km s^{-1} Mpc^{-1}, Kepler's supernova is out in the galactic halo *beyond* the galactic nucleus at a distance of 12.1 kpc and at $Z = 1.4$ kpc). The optical remnant of Kepler's supernova (see fig. 17) consists of a fan-shaped region containing a number of bright knots. A few fainter filaments are also present. Intercomparison of 200-inch plates taken during the last 20 years shows that the brightest part of the optical remnant is moving *bodily* towards the NW with a velocity ~0″.03 per year. At an assumed distance of 10 kpc this corresponds to a velocity ~1400 km sec^{-1}. Minkowski's (1959) observations yield radial velocities $-275 < v < -140$ km s^{-1}, so that the optical knots must be quite near the *edge* of the shell of Kepler's supernova. (The spectrum shown on fig. 18 yields a radial velocity $v = -230$ km s^{-1}.) The observed velocities of the ejecta from Nova Ophiuchi 1604 are surprisingly low. The fact that this remnant is located ~1 kpc above the galactic plane shows that the expanding supernova shell cannot have been slowed down by interstellar gas. Intercomparison of 200-inch plates taken at different epochs shows that the time scale for changes in the bright knots in Kepler's supernova remnant is ~10 years. This value is comparable to the (recombination) time scale in the moving knots of Cas A, in which $n_e \geq 2 \times 10^3$ cm^{-3} (van den Bergh 1971*c*). Observations with the nebular spectrograph of the Lick 120-inch (3-m) telescope show that, in all knots emitting [S II], $I(6731) > I(6717)$ (see fig. 18 [pl. 18]). This observation implies (Krueger, Aller, and Czyzak 1970) that $n_e > 30\, T_e^{1/2}$ in the [S II] emitting regions, i.e., $n_e > 3 \times 10^3$ cm^{-3} for $T_e = 1 \times 10^4$ °K. This high density in the knots comprising the remnant of Kepler's supernova strengthens the conclusion that these knots could not have been decelerated significantly.

Detailed studies of the expansion of the remnant of Kepler's supernova are rendered difficult by the fact that this object is located at a low southern declination where the seeing is usually poor. None of the Palomar plates taken in recent years matches Baade's superb 1950 plate which is shown in this atlas.

Low-resolution radio observations of Kepler's supernova remnant are reported by Milne (1969). More recent radio observations by Hazard and Sutton (1971) suggest that 3C 358 consists of a broken shell comprising two components or of two concentric shell-shaped sources. The diameter of the radio source is ~3′, so that the expansion velocity of the radio shell must be 150″/(1970–1604) ≃ 0″.4 per year. The corresponding expansion velocity is $\sim 2 \times 10^4$ km s^{-1}, i.e., an order of magnitude greater

1973ApJS...26...19V

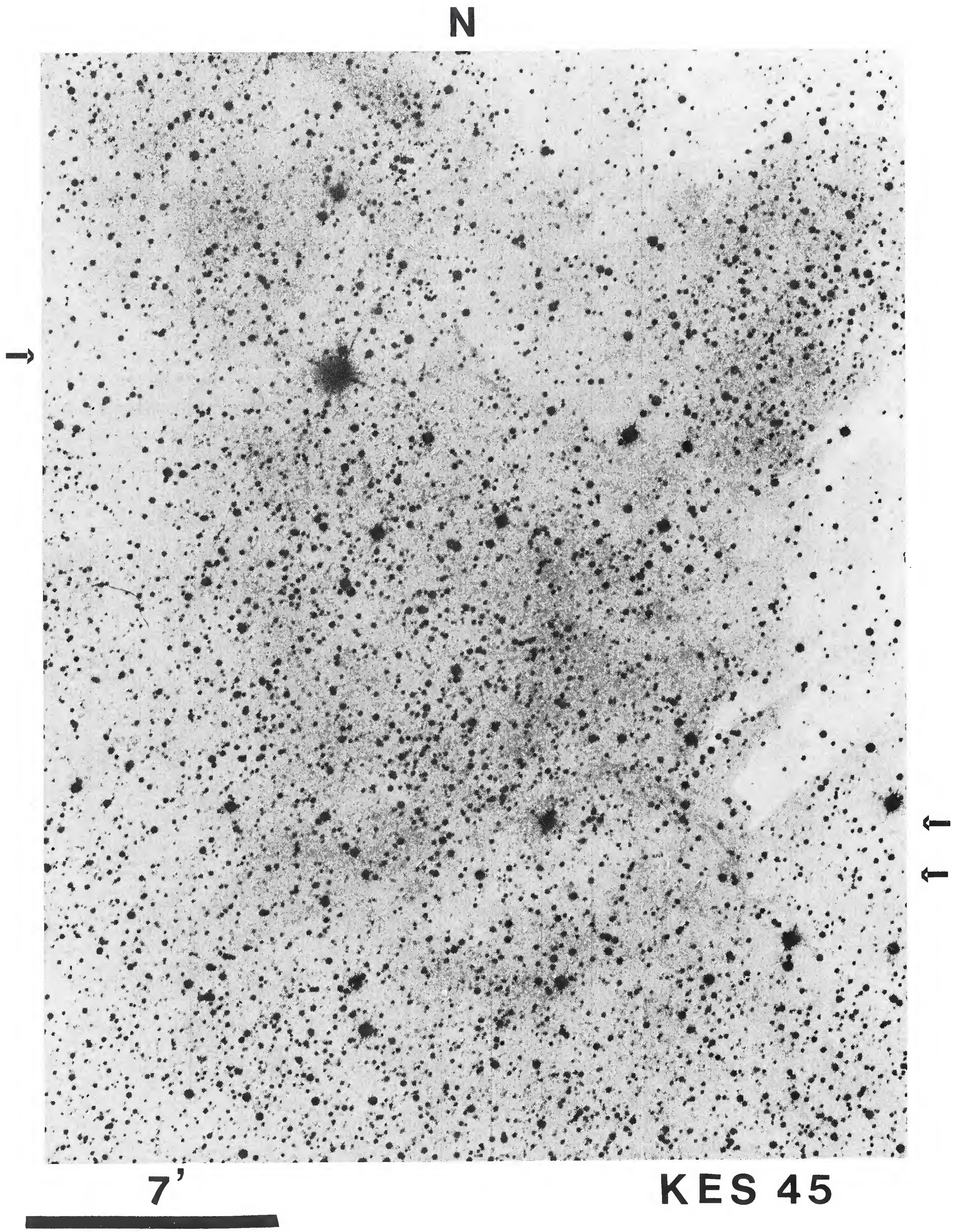

FIG. 16

VAN DEN BERGH *et al.* (*see* page 28)

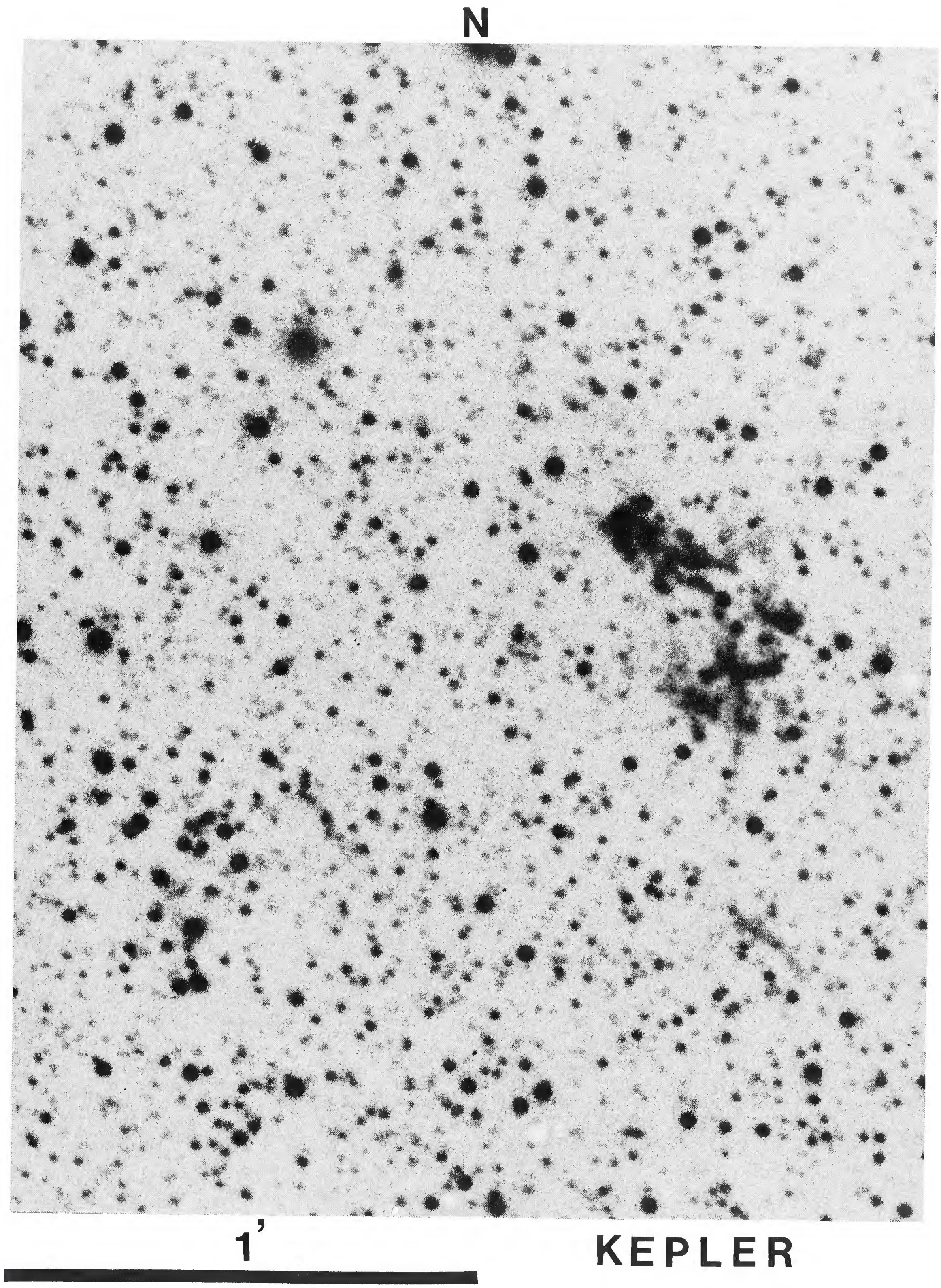

FIG. 17

VAN DEN BERGH *et al.* (*see* page 28)

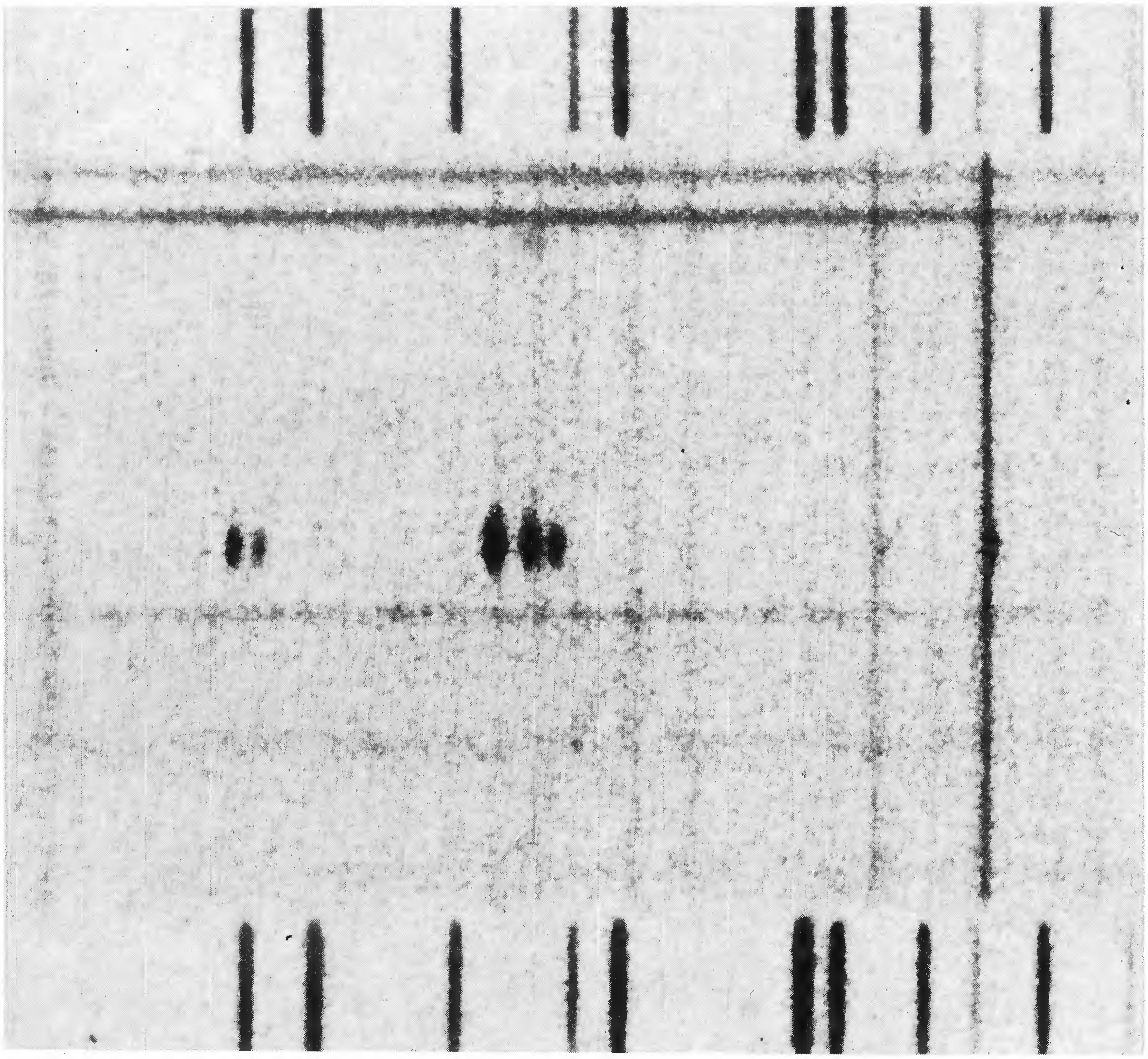

FIG. 18.—Spectrum of the brightest knots in the remnant of Kepler's supernova obtained with the prime-focus spectrograph of the Lick 120-inch telescope.

VAN DEN BERGH *et al.* (*see* page 28)

than the velocity of the optical knots. Possibly these apparently conflicting observations could be reconciled by a model in which the optical knots are regarded as the remnant of a shell that was ejected at low velocity *before* the main explosion of Kepler's supernova took place. (Alternatively it might be assumed that the supernova shell transferred momentum to a stationary circumstellar shell.) Van den Bergh (1971*c*) had previously suggested that the quasi-stationary flocculi in Cas A might also represent compressed *circumstellar* material. It should, however, be emphasized that the system of flocculi in Cas A does not show any expansion whereas the knots in the remnant of Kepler's supernova do exhibit a systematic outward motion.

It is remarkable that the supernovae of 1572 and 1604, which were both of Type I (Minkowski 1966), have produced such very different optical remnants. In particular the remnant of Tycho's supernova does not contain any nebulosity that resembles the slowly expanding fan of flocculi associated with Kepler's supernova.

s) *W28* (see pl. 19)

The crisp optical filaments associated with Westerhout 28 were first noticed by van den Bergh (1960). An intermediate-band Hα interference-filter photograph of this nebula is shown in figure 19. This plate shows a heavily obscured extended emission region within which are located a number of crisp filaments. A narrow-band interference-filter photograph of the central part of W28 has been published by Courtès, Véron, and Viton (1964). This remnant may resemble Kesteven 45, which also consists of filaments that appear to be embedded in emission nebulosity. Excellent radio maps of W28 have been obtained by Kundu (1970), by Milne and Wilson (1971), and by Shaver and Goss (1970). The radio-isophotes might be interpreted as an incomplete shell of radius $\sim 15'$ centered at $\alpha_{1950} \simeq 17^h57^m\!.6$, $\delta_{1950} \simeq -23°25'$. The nonthermal nature of W28 is supported by the spectral index $\alpha = -0.4$ and by the occurrence of strong polarization (Milne and Wilson 1971). The distance to W28 has not been established with any degree of certainty (T. L. Wilson 1972).

t) *3C 400.2 = HC 42* (see pl. 20)

This exceedingly faint supernova remnant is only barely visible on a two hour 48-inch Schmidt plate taken through an Hα interference filter. The image structure may suggest that some exceedingly faint filaments are present in this remnant.

u) *DR 4 = γ Cygni Nebula = W66* (see pl. 21)

The radio source DR 4 (Downes and Rinehart 1966; Higgs and Halperin 1968, and references therein) is one of the brightest components of the Cygnus X complex. It consists of a central source that has a diameter $\lesssim 3'$, which is superposed on a more extended emission region (W66) with a diameter $\sim 8'$. The position of the central source, $\alpha_{1950} = 20^h20^m38^s \pm 2^s$, $\delta_{1950} = +40°03'24'' \pm 20''$, is essentially identical to that of the γ Cyg nebula (Drake 1959; Pike and Drake 1964) which is located at $\alpha_{1950} = 20^h20^m40^s$, $\delta_{1950} = 40°04'15''$. A physical association between the nebula and γ Cyg, which is of spectral type F8 Ib, is improbable. Figure 21 shows[1] that the γ Cyg nebula, which is situated slightly SE of the star, does *not* exhibit the crisp filamentary structure that is diagnostic of supernova remnants. Nevertheless, the close positional agreement of the nonthermal radio source, which has a spectral index $\alpha = -0.69 \pm 0.11$ (Higgs and Halperin 1968), and the optical nebula lends considerable support to the identification.

It has been pointed out previously (van den Bergh 1960) that a vast system of crisp filaments covering a large part of Cygnus is roughly centered on γ Cyg.

[1] The dark marking NW of γ Cyg is a plate flaw.

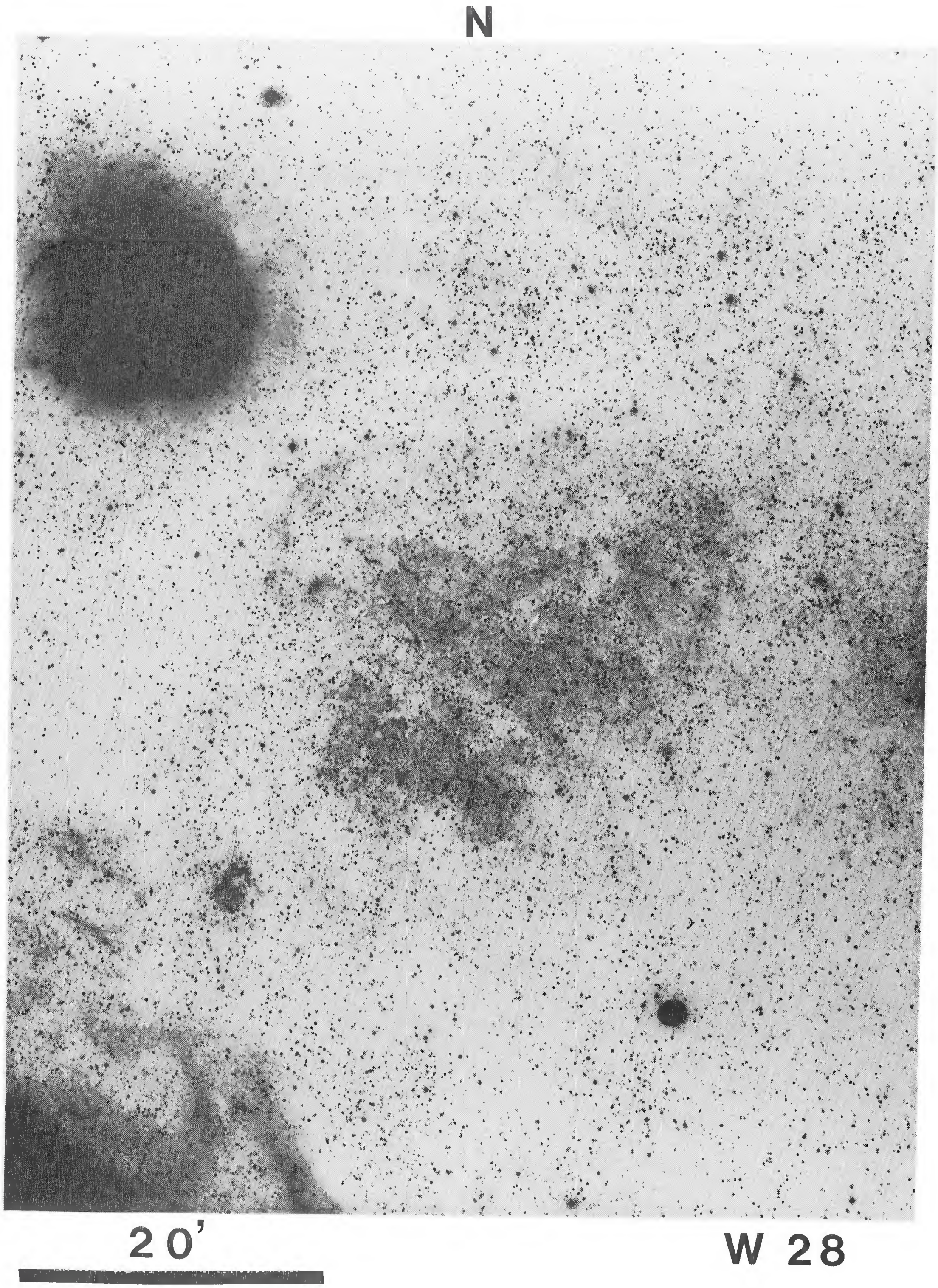

FIG. 19

1973ApJS...26...19V

PLATE 20

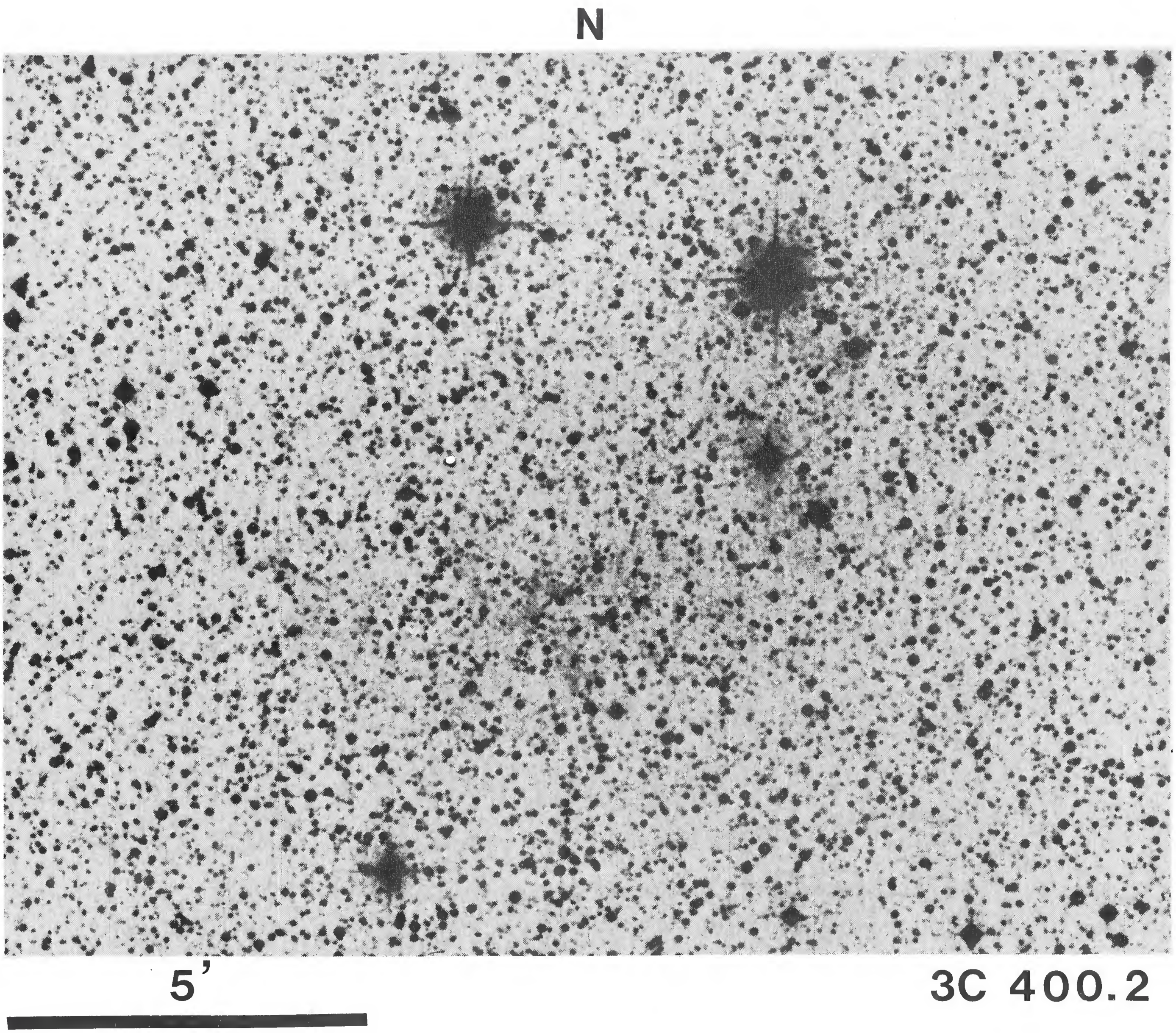

FIG. 20

VAN DEN BERGH *et al.* (*see* page 29)

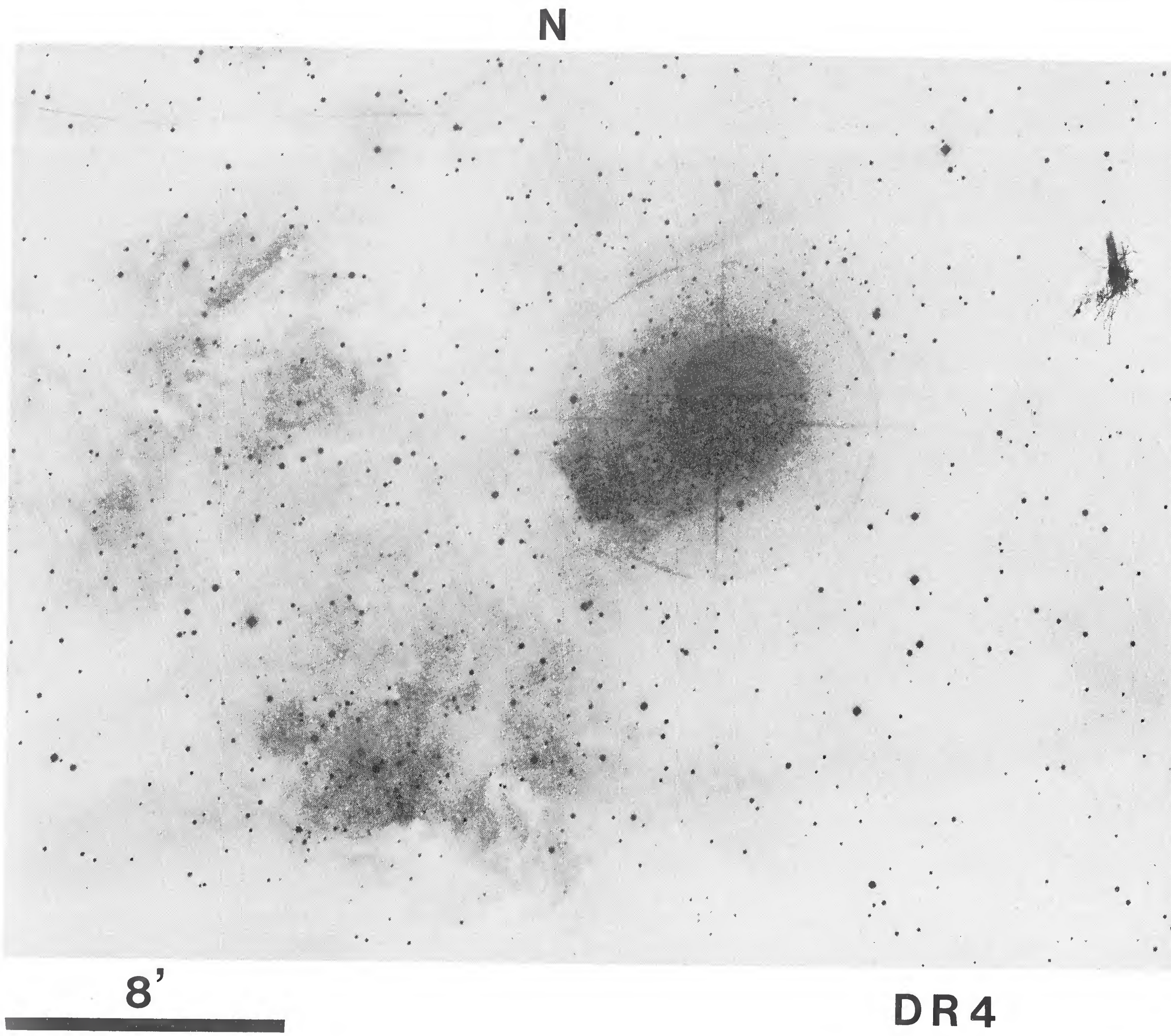

FIG. 21

VAN DEN BERGH *et al.* (*see* page 29)

v) *The Cygnus Loop = Veil Nebula = NGC 6960, 6979, and 6992–5* (see pl. 22)

The Cygnus Loop consists of large numbers of bright delicate filaments. Most of these filaments appear to form an incomplete shell with radius $\sim 80'$ centered at $\alpha_{1950} = 20^h49^m.5$, $\delta_{1950} = +30°45'$. This shell is no doubt brightest where it collides with interstellar gas clouds. This view is confirmed by star counts which show a much larger number of stars outside (to the west) of NGC 6960 than to the east of it. In the southern part of the remnant filaments extend to distances $\sim 130'$ from the center of the shell. Possibly the gas density in this direction is low so that the expansion of the supernova has not been slowed down quite as much as it has in other directions.

Excellent radio maps of the Cygnus Loop have been published by Hogg (see Minkowski 1968), by Moffat (1971), and by Kundu and Becker (1972). These observations show a close correspondence between the optical filaments and the brightest parts of the radio shell. In this respect the Cygnus Loop resembles such other old supernova remnants as IC 443. Kundu (1969) has found strong polarization in some parts of the radio shell that constitutes the radio remnant of the Cygnus Loop.

Considerable temperature stratification is found within individual filaments. From observations of the [N II] lines Parker (1967) obtains $T \simeq 1.5 \times 10^4$ ° K, whereas Parker (1969) obtains $T \simeq 3.3 \times 10^4$ ° K from the lines of [O III]. From the [O II] intensity ratio $I(3726)/I(3729)$ Osterbrock (1958) finds that the brightest filaments in the Cygnus Loop have densities $n_e \sim 300$ cm^{-3}. This rather low density, together with the small observed thickness and high surface brightness, suggests that the filaments in the Cygnus Loop are sheets seen edge-on. A detailed theoretical interpretation of the Cygnus Loop is given by Cox (1972*a*, *b*, *c*).

Hubble (1937) has found that the Cygnus Loop is currently expanding at a rate of 0".03 per year. Radial-velocity observations by Minkowski (1958) and by Doroshenko (1970) suggest that the Cygnus Loop consists of a thick shell with an outer velocity ~ 113 km s^{-1}. Equating Hubble's proper motion for the outer part of the shell to this velocity yields a distance of ~ 800 pc.

Soft X-rays from a region with dimensions $\sim 3°$ centered on the Cygnus Loop have been observed by Grader, Hill, and Stoering (1970) and by Gorenstein *et al.* (1971). Bleeker *et al.* (1972) find that the X-ray spectrum of the Cygnus Loop is best represented by thermal bremsstrahlung from a plasma at 2.7×10^6 ° K. The expected coronal emission line λ5303 of [Fe XIV] has been searched for but not found by Kurtz, Vanden Bout, and Angel (1972).

w) *Cassiopeia A = 3C 461* (see pls. *23a* and *23b*)

The optical remnant of Cas A was first described by Baade and Minkowski (1954). Their observations showed that this supernova remnant consists of two distinct components: (1) a system of fast-moving knots and (2) a number of quasi-stationary flocculi.

Two photographs of Cas A taken in September 1972 are shown in figures 23*a* and 23*b*. Comparison of these plates with earlier photographs (Baade and Minkowski 1954; van den Bergh 1971*c*) shows that significant changes have taken place during the last 20 years. The brightest filament in the NE part of the remnant, which has internal velocity dispersion ~ 3000 km s^{-1}, has recently broken up into a number of distinct knots. The southern part of the remnant, which was essentially free of moving nebulosity 20 years ago, now exhibits a number of fast-moving knots. The overall appearance of the bright arc of nebulosity forming the northern part of the shell of Cas A has changed little during the last two decades, even though most individual knots in this region have lifetimes of only ~ 10 years. More diffuse moving nebulosity occurs in the eastern part of Cas A. Very fast-moving knots continue to occur near the ex-

1973ApJS...26...19V

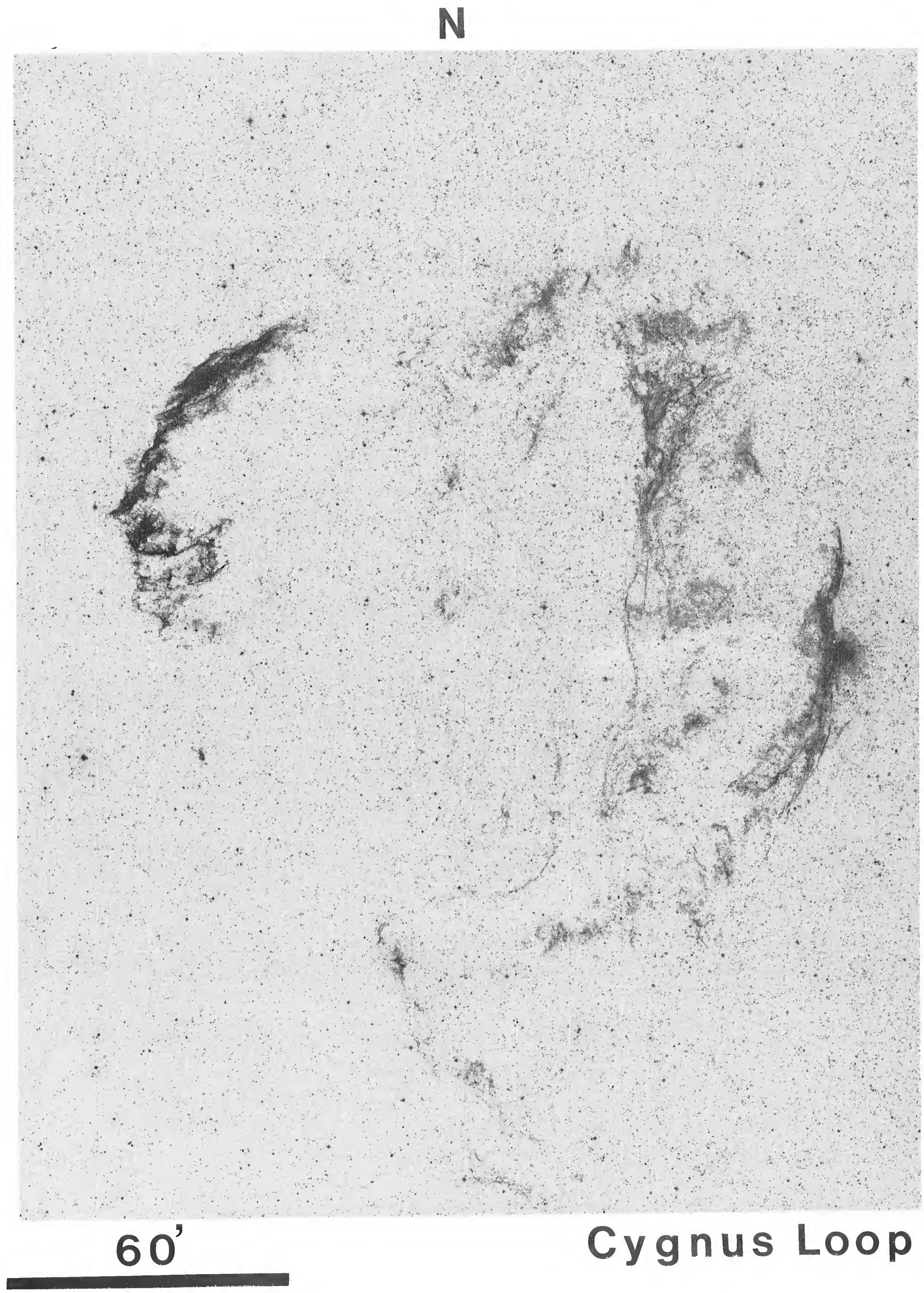

FIG. 22

VAN DEN BERGH *et al.* (*see* page 30)

PLATE 23*b*

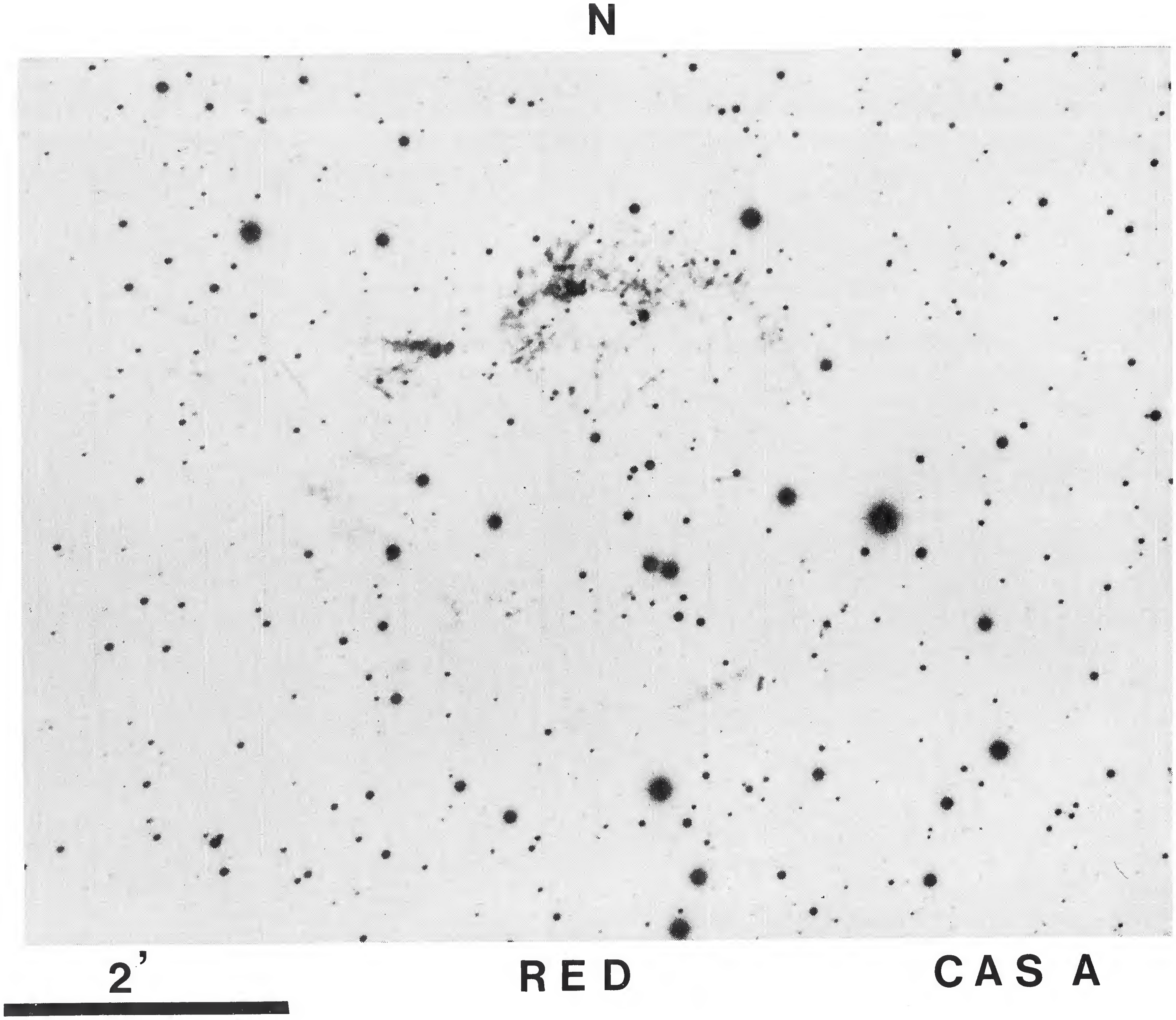

FIG. 23*b*

VAN DEN BERGH *et al.* (*see* page 30)

TABLE 4

CHEMICAL ABUNDANCE IN A FAST-MOVING KNOT IN CAS A*

Ar/O	S/O	Ne/O	N/O	H/O†	H/O‡	He/O†
+0.05	+0.11	< −0.40	< −1.44	< −1.64	< −1.46	< −0.14

* All abundances given in log $N(X_1)/N(X_2)$ relative to those of the Orion Nebula.

† Case B assumed (see Peimbert and van den Bergh 1971).

‡ Case A assumed (see Peimbert and van den Bergh 1971).

treme northeastern corner of the remnant. These fast-moving knots live outside the radio shell of Cas A (Rosenberg 1970*a*, *b*). For one of these knots (van den Bergh 1971*c*) $V > 9520$ km s^{-1}. A system of faint radial streaks appears to be associated with these fast-moving knots.

The spectra of moving knots and of quasi-stationary flocculi are entirely different. The moving knots exhibit emission lines of [O I], [O II], [O III], [S II], and [Ar III] (van den Bergh 1971*c*) whereas the quasi-stationary flocculi show only [N II] and Hα in emission. According to Peimbert and van den Bergh (1971) the abundances in Cas A are those given in table 4. These data show that oxygen, argon, and sulfur are overabundant with respect to hydrogen and nitrogen by at least a factor of 30. This observation constitutes the most direct evidence that is yet available in favor of the hypothesis that nucleosynthesis takes place in supernovae. Intercomparison of figures 23*a* (green) and 23*b* (red) shows that the quasi-stationary flocculi, which emit Hα and [N II] λλ6548, 6584, are visible only in red light. About 30 of these quasi-stationary flocculi can be seen on 200-inch telescope plates taken in good seeing. Similar plates reveal the existence of ~100 knots of fast-moving nebulosity. There appears to be no direct connection between any of the moving knots and the quasi-stationary flocculi.

According to van den Bergh and Dodd (1970) the explosion that produced Cas A took place in 1667 ± 8. The explosion of this supernova was *not* seen by seventeenth century observers. This result strongly suggests that $V(\max) > 0$. From the ratio of the auroral to the transauroral lines of [S II] in the moving knots Searle (1971) obtains $A_V = 4.3$. For an assumed distance of 2.8 kpc (van den Bergh and Dodd 1970) the luminosity of Cas A becomes $M_V(\max) > -16.5$. This value is not inconsistent with the result of Kowal (1968) who finds $M_{pg}(\max) = -16.5 + 5\log(H/100)$ for supernovae of Type II. These supernovae are believed to result from the explosion of massive young stars. Such stars often occur in associations. No OB stars have, however, been found in the vicinity of Cas A (van den Bergh 1971*b*). Some faint emission nebulosity near Cas A *might* represent a fossil Strömgren sphere. The amount of energy required to ionize such an H II region would be 5×10^{48} ergs (Peimbert 1971). The total mass of all the moving knots that are visible *at the present time* is only $\sim 0.05\,\mathfrak{M}_\odot$. This observation does not place any useful limits on the mass of the star that produced Cas A.

The fast-moving knots in Cas A exhibit a wide range of space velocities. For an assumed distance of 2.8 kpc these knots have space velocities of $4140 > v > 8460$ km s^{-1}. The low abundance of hydrogen in these knots shows that the observed velocity range cannot be due to deceleration of the slowest moving knots by (hydrogen-rich) interstellar clouds. Within Cas A filament No. 1, individual knots exhibit radial-velocity differences of up to 3000 km s^{-1}. These velocity differences *cannot* be due to differing ejection velocities from the supernova because knots with such strongly differing space velocities could not have remained together in one filament for ~300 years. The only alternative appears to be that individual knots are still being accelerated (or decelerated) at the present time. The possibility that these effects are produced by the stellar(?) remnant of the supernova cannot yet be excluded. No star with

$V < 22.5$ is visible within 8 standard deviations of the center of expansion of Cas A (van den Bergh and Dodd 1970). Adopting a distance of 2.8 kpc and $A_V = 4.3$ mag (Searle 1971) yields $M_V > +6$ for any stellar remnant of this supernova.

For temperatures $T > 6200°$ K Peimbert and van den Bergh (1971) find that the nitrogen-to-oxygen ratio in quasi-stationary flocculi is higher than that prevailing in the Orion Nebula. *If* this result is correct, then the quasi-stationary flocculi cannot represent interstellar gas that was trapped by the expanding supernova shell. The observed overabundance of nitrogen might be understood by assuming that the quasi-stationary flocculi were formed by compression of a circumstellar shell. Such circumstellar material might have been enriched in ^{14}N that was produced in the CNO bi-cycle.

High-resolution radio maps of Cas A have been published by Rosenberg (1970*a*, *b*). His data show that the remnant of Cas A consists of a relatively well-defined shell with an outer radius ~130″. A few isolated radio peaks occur out to a distance of ~150″. Intercomparison of the optical and radio data shows that there is no *detailed* correspondence between the positions of the brightest optical knots and individual radio hot spots. This lack of detailed coincidence is puzzling because the brightest knots and radio hot spots both occur at a distance of ~105″ from the center of the remnant. In this respect Cas A, which is very young, differs from such old supernova remnants as IC 443 and the Cygnus Loop in which the brightest optical filaments coincide with the brightest parts of the optical shell.

Observations by Rosenberg (1970*b*) show linear polarization ~5 percent. This radio polarization indicates that the magnetic field in Cas A is radial. In this respect Cas A resembles Tycho's supernova remnant in which the existence of a radial magnetic field is also suggested by the polarization observations of Baldwin *et al.* (1970).

Table 5 shows that the position of the center of expansion of Cas A, as derived by van den Bergh and Dodd (1970), is in excellent agreement with the position of the geometrical center of the radio shell (Rosenberg 1970*b*).

X-rays from Cas A were first detected by Friedman *et al.* (1967). This is *Uhuru* source 2U 2321+58. No radio pulsar has been discovered so far in the direction of Cas A.

x) *CTB 1* (see pl. 24)

This source was discovered by Wilson and Bolton (1960) and identified with a faint ring of filamentary nebulosity by van den Bergh (1960). Radio maps of CTB 1 have been published by Willis and Dickel (1971). Comparison of these maps with our figure 24 shows that most of the radio radiation is emitted from the region that is located within the optical remnant. The radio shell of CTB 1 appears brightest where the optical filaments are brightest. In this respect CTB 1 resembles such other old supernova remnants as IC 443 and the Cygnus Loop. The nonthermal nature of CTB 1 is weakly supported by its spectral index $\alpha = -0.49 \pm 0.50$ (Willis and Dickel 1971) and more strongly by the presence of polarization of up to 10 percent. No obvious stellar remnant is visible near the center of CTB 1.

TABLE 5

POSITION OF CASSIOPEIA A

	α(1950)	δ(1950)
Geometrical center of main radio shell	$23^h21^m10^s$	+58°32′22″
Optical center of expansion	23 21 11	+58 32 19

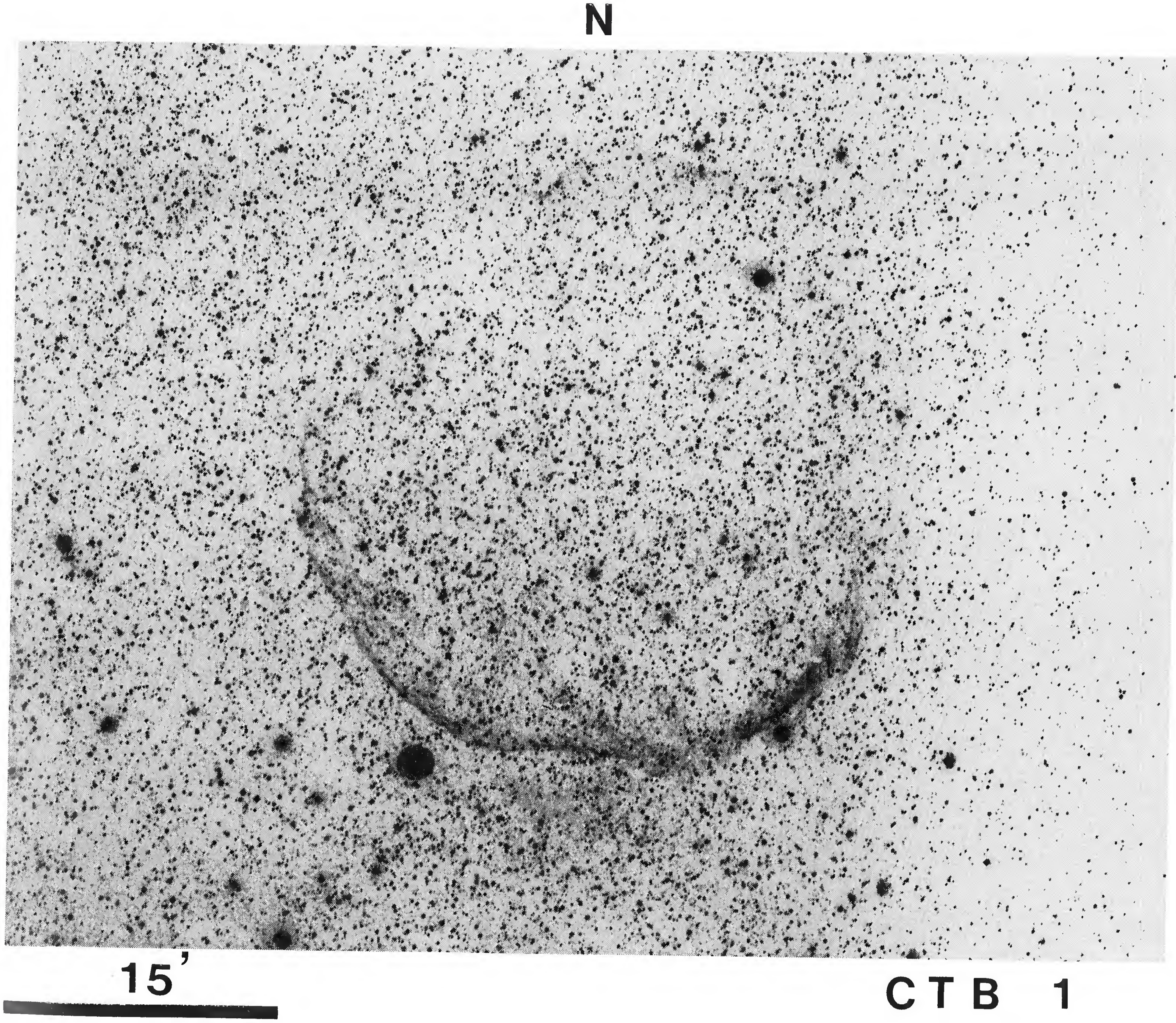

FIG. 24

VAN DEN BERGH *et al.* (*see* page 32)

It is rather remarkable that the optical shell of CTB 1 is morphologically almost indistinguishable from the filamentary shell that surrounds the sixth-magnitude WN5 star HD50896.

III. CLASSIFICATION OF SUPERNOVA REMNANTS

In an observational science such as astronomy, the classification of any species of objects into various subgroups is often the first step to a deeper understanding of the nature of the species being studied (Batten 1967). In the case of supernova remnants the classification problem is rendered particularly difficult because (1) the observed remnants have ages that differ by factors of at least 100 and (2) the appearance of a remnant will depend on the nature of the interstellar environment in which the supernova explosion took place.

A purely empirical classification of supernova remnants is given below. It is hoped that future work will be able to throw some light on the physical basis of this classification scheme.

a) *Cygnus Loop Type*

The Cygnus Loop, IC 443, RCW 86, and possibly RCW 103 are examples of a type of remnant in which an incomplete shell is outlined by very sharp filaments of intermediate length. The brightest filaments occur where the supernova shell runs into relatively dense interstellar clouds. The spectacular shell-shaped nebula N70 in the Large Magellanic Cloud (Evans and Thackeray 1950) might be of the same type, although radio radiation has not yet been detected from it.

b) *S147 Type*

The Vela remnant is the only other object of this class that is presently known. This type of remnant is characterized by the presence of very long delicate filaments. It seems probable that these filaments are luminous sheets seen edge-on. The remnant of Tycho's supernova also exhibits such filaments. The age difference between S147 and Tycho is so great that it is premature to speculate on the possibility that these objects might be of a related type.

c) *Diffuse Shell Type*

The Monoceros Ring, OA 184, HB 3, and HB 9 are examples of the diffuse shell type of remnant. Typically objects of this type contain a few sharp filaments in addition to a larger number of more diffuse filaments. VRO 42.05.01 and CTB 1 might *possibly* be of the same type. Perhaps some of the high-latitude "spurs" (see fig. 28 of Meaburn 1970) are related to this class of remnant.

d) *W28 Type*

Both RCW 89 and W28 consist of shells that are filled with filamentary nebulosity.

e) *Unique Remnants*

The Crab Nebula remains unique. A possible counterpart is 3C 58, which has so far eluded optical detection. The fan-shaped optical remnant of Kepler's supernova has a very low expansion velocity similar to that of the Crab. The knots and arcs of nebulosity in Pup A are vaguely reminiscent of the quasi-stationary flocculi in Cas A and the fan-shaped nebula associated with Kepler's supernova. The unique behavior of the remnant of Cas A is, no doubt, due to its extreme youth. Among supernova remnants the γ Cyg nebula (DR 4) is unique because it does not exhibit filamentary structure.

f) *Unclassified Remnants*

3C 400.2 is too highly obscured to make classification possible. In the case of MSH 10−5*3* and Kes 45 only a few more or less isolated filaments are visible.

We wish to thank Professors Bok, Minkowski, and Westerlund for making prints of their plates of supernova remnants available to us. Thanks are also due to Drs. Dickel and Willis for making some of their radio observations available to us. One of us (S. v.d.B.) wishes to acknowledge the kind hospitality of the Hale Observatories and the Lick Observatory. This investigation was partly supported by the National Research Council of Canada, and by the National Astronomy and Ionosphere Center which is operated by Cornell University and supported by the U.S. National Science Foundation. Special thanks are due to Mr. Anson Moorhouse who made most of the prints shown in this *Atlas* and to the Hale Observatories for permission to reproduce atlas prints from their plate files.

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