13 July 1962, Volume 137, Number 3524 **SCIENCE**

The Story of the Crab Nebula

Ancient records reveal its origin as a supernova; recent work indicates it is a cosmic synchrotron.

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The Crab Nebula has a history of discovery and of observation that more closely resembles a tale of mystery and imagination than a sober, scientific recital. For example, if we approach the subject by consulting Dreyer's *New General Catalogue of Nebulae and Clusters*, we find that the Crab Nebula is number 1952 in the list, that it is also designated as Messier 1, and that its discovery is attributed to "Bevis, 1731." This simple entry gives no details of discovery, and I have not been able to find the record, despite intermittent searches during the past 25 years. My bookworming, however, disclosed that John Bevis was an English physician whose avocational activities in astronomy equaled the activities of contemporary professionals (*1*). He had his own private observatory, reported numerous astronomical observations to the Royal Society, had his name proposed by friends as a candidate for Astronomer Royal, and died from a fall on the stairway of the building that housed his small telescope—in the Wild West tradition, he died with his boots on.

Before Bevis died, in 1771, he prepared for publication a very elaborate set of star charts, the rare *Uranographia Britannica*. On these, he plotted not only many stars from his own observations but also the 16 nebulae known in his time. The cost of the engravings was so high, however, that the printer went bankrupt, and the creditors won a lawsuit that gave them the assets, including the plates of the *Uranographia Britannica.* Although the publisher thus lost the engravings, he managed to give Bevis some proofs or complimentary copies, which were shown to the French historian Lalande in London in 1763. Many years later, in 1786, the plates probably were used for the *Atlas Celeste*, which was published without credit to Bevis (*2*). Of the few copies of the *Atlas* that are extant, and which I have examined, none gives details of Bevis's discovery of the Crab Nebula.

The Crab Nebula is known also as Messier 1 (M1) because Charles Messier, Louis XV's *"ferret de comètes,"* independently discovered it in 1758. In that year he was looking for the first predicted return of Halley's Comet. Instead, he discovered another bright one whose path took it close to the position of the Crab Nebula. He wrote (*3*), "The comet of 1758, the 28th of August, being between the horns of the Bull, I discovered below the southern horn and a short distance from the star zeta of that constellation, a whitish light, elongated in the form of the light from a candle, not containing any star" (Fig. 1). Later, in 1771, when he published his first list of nebulae, we find the note, "Observed by Dr. Bevis about 1731. It is reported in the English *Atlas Celeste*" (Fig. 2). Thus Messier, who, Lalande states (*4*), also had some *Atlas* proofs, graciously gave Bevis priority for discovery of the first nebula in the first important catalogue of nebulae (*5*).

Visual observations of the Crab Nebula during the next hundred years did not contribute much significant information about it. Some of the most expert observers, including the Herschels (*6*), thought it could be resolved into stars. Lord Rosse (*7*), observing with his largest reflector, pointed out the filamentary character of the nebula but thought it would prove to be a star cluster if examined with an instrument of greater power. Lassell (*8*), observing under the clearer Mediterranean sky at Malta, was not fooled by the stars; he noted that the faint ones seen over the nebula are no more numerous than those in the adjacent areas of the Milky Way. It was also about this time, the mid-19th century, that the nebula became known by its present name. In 1844 Lord Rosse had published a drawing of the object that made it look much like a bug (*7*, plate XVIII, Fig. 81), and in 1848 he had referred to it as a "crab." For unknown reasons, this description met with general acceptance, and the name has clung with a tenacity commendable in any normal crab.

Astronomical Photography

The development of astronomical photography revolutionized the study of nebulae, and the case of the Crab Nebula is one of the best examples. Isaac Roberts first photographed it in 1892 with his 20-inch reflector (*9*). He reported that his picture hardly resembled any of the drawings (he found this to be generally true as he continued his pioneering celestial photography). Later, similar work by Keeler, Curtis, and Ritchey, with increasingly better and larger reflectors, demonstrated that the Crab Nebula, with its roughly oval form and peculiar filamentary structure, has no counterpart among the thousands of known nebulae.

In the next most significant step in the study of the Crab Nebula, Lampland (*10*) in 1921 reported changes in the appearance of the nebulosity, which on

The author is director of Kitt Peak National Observatory, Tucson, Ariz. This article is based on an address that he delivered, as retiring vice president of Section D of the AAAS, during the Denver meeting.

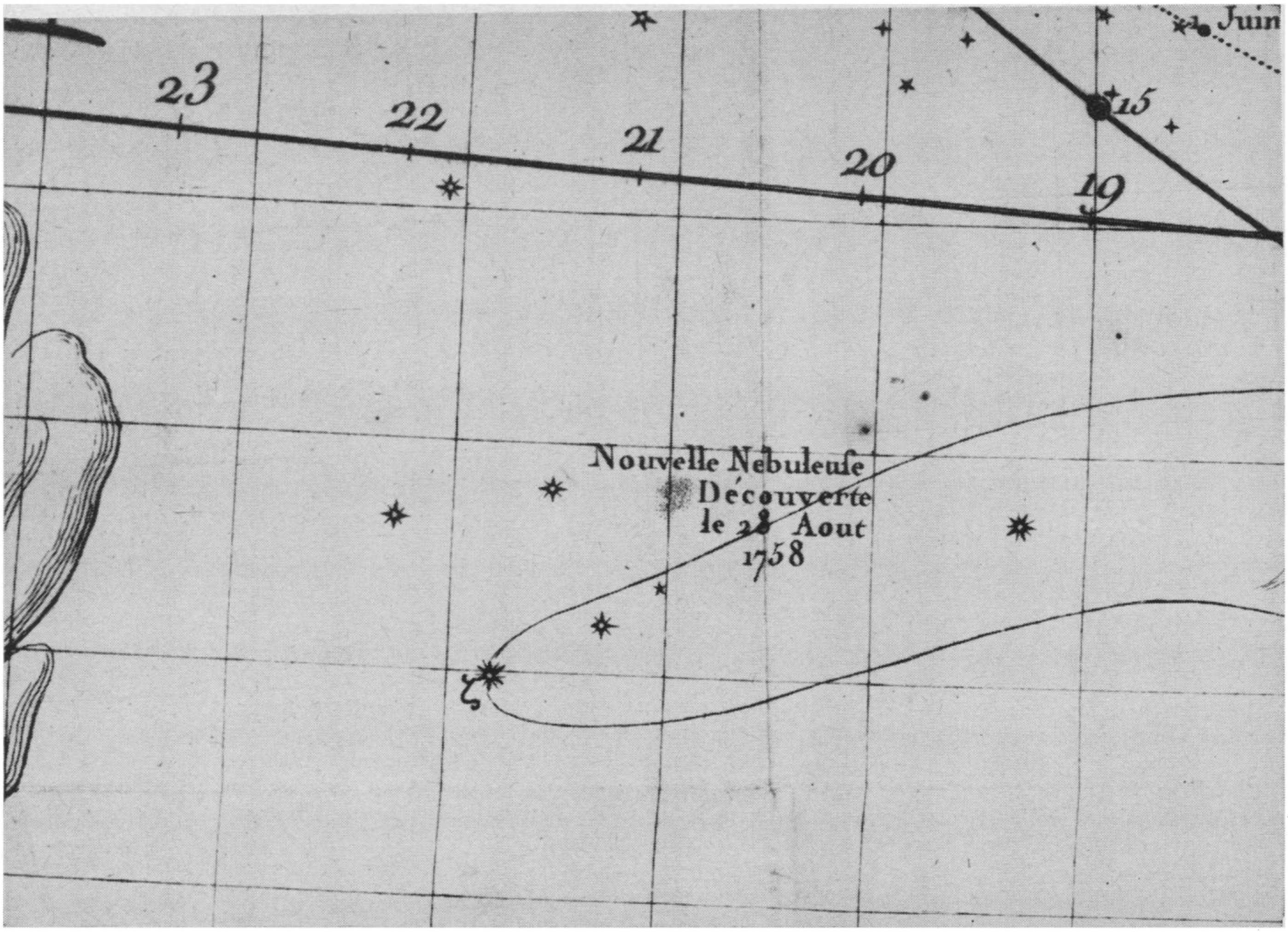


Fig. 1. Enlarged portion of Charles Messier's chart of the path of the comet of 1758 (the line with numbered marks 19 to 23), showing the discovery position of the Crab Nebula, near the star zeta Tauri in the southern horn of the Bull.

the scale of his plates could be interpreted either as changes in brightness or as motions, or as a combination of the two. Duncan decided to measure these changes on a pair of 60-inch Mount Wilson reflector plates taken 11½ years apart. He found (*11*) that 12 of the outer filaments had moved radially from the center (Fig. 3). Thus there emerged, in 1921, the very important finding that the Crab Nebula is *expanding*. The finding was important because expanding nebulae had previously been discovered by Barnard (*12*) around two novae—in 1917 around Nova Persei (1901) and in 1918 around Nova Aquilae (1918).

The Nova of 1054

In the same year (1921), by a remarkable coincidence, the Swedish astronomer Lundmark (*13*) published a list of suspected novae recorded in ancient Chinese chronicles. For No. 36 in that list we find the date of appearance given as 4 July, A.D. 1054, the position as "southeast of eta Tauri but near," and the duration of visibility as 6 months. In a footnote Lundmark put the punch line: "Near NGC 1952." However, the nearby star is zeta, not eta, Tauri, and this unfortunate printer's error was not corrected until 17 years later (*14*).

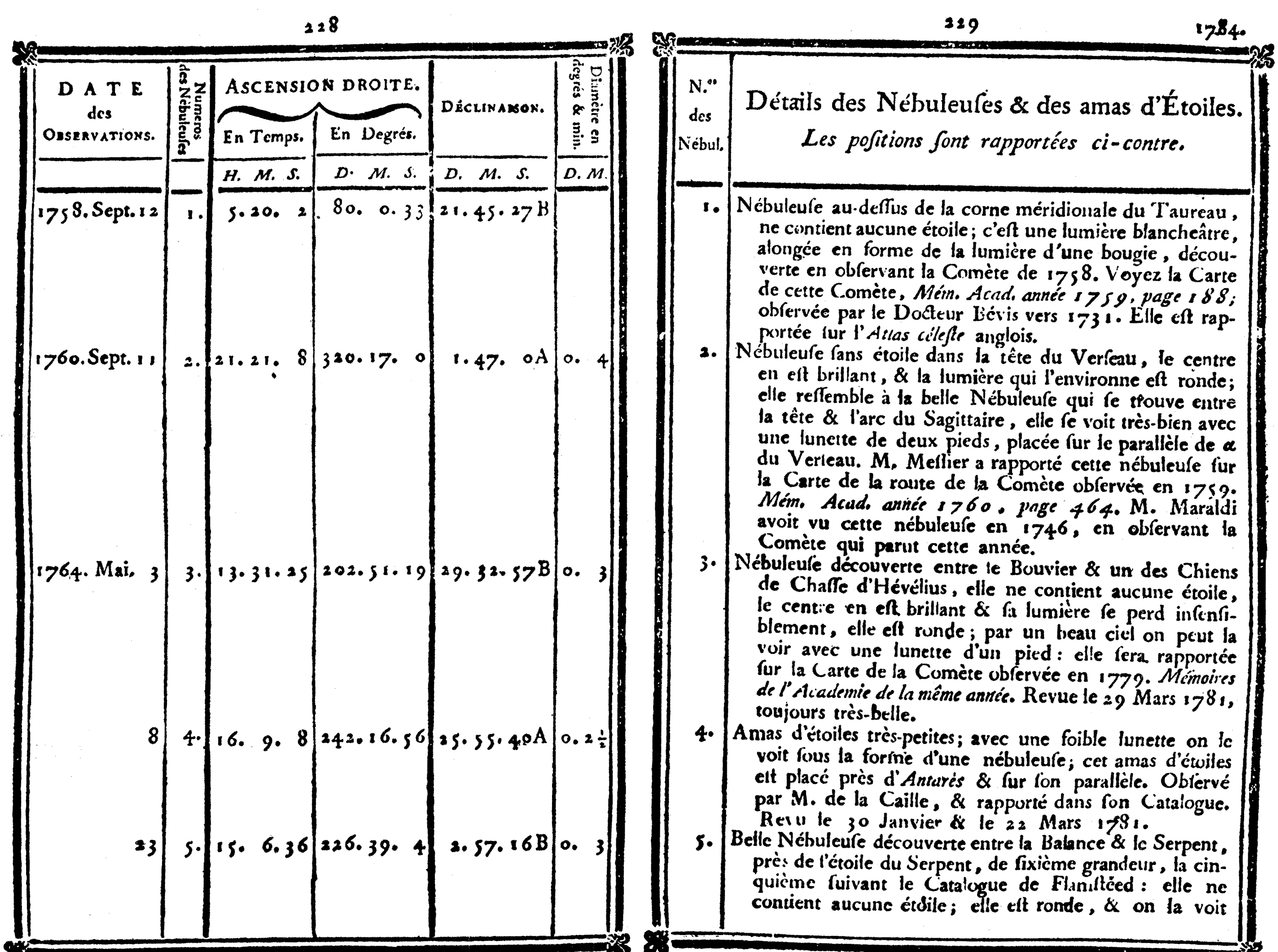
While the idea that nova outbursts eject nebulosity was not new 40 or 50 years ago, it seems to be a strange fact that none of those who investigated the Crab Nebula ventured to suggest a nova origin for it. Thus, neither Lampland nor Duncan, who respectively detected and measured its expansion, nor Lundmark, who noted the correspondence in position between it and a suspected nova that had been observed by the Chinese, mentioned this possibility. Furthermore, none of these investigators referred to the spectroscopic observations of double emission lines reported in 1915 by Slipher (*15*), a colleague of Lampland's, and in 1918 by Sanford (*16*), a colleague of Duncan's. Nevertheless, part of the puzzle was put together in 1928 when Hubble (*17*), with characteristic genius for getting something new from nebulae, noted that the Crab Nebula's size and rate of expansion indicated that it had originated about 900 years before. As the clincher, he cited Lundmark's work which gave the agreement in time and position between the Crab Nebula and the nova recorded by the ancient Chinese. Unfortunately, this inspired inference by Hubble was published as an Astronomical Society of the Pacific *Leaflet*, and *Leaflet's* were written for, and chiefly read by, the lay members of the society, and it appears that Hubble's remark escaped the serious attention of most of the contemporary old pros.

Some more pieces of the Crab Nebula puzzle were put together when the spectrum of the nebula as a whole was obtained with the Crossley nebular spectrograph at Lick Observatory in

1937 (*18*) (Fig. 4). These showed that the double emission lines observed by Slipher, and the large positive and negative radial velocities measured by Sanford, are simply the result of a roughly ellipsoidal shell of gas that is expanding with a velocity of the order of 1000 kilometers per second. When the slit of the spectrograph was long enough to extend across the nebula, bow-shaped lines were obtained. Spectra of Nova Persei (1901) (*19*) and of Nova Aquilae (1918) (*20*) show similar effects from these expanding nebulae (Figs. 5 and 6). These lines are widely double in the center, where the maximum radial velocities of recession, from the back, and of approach, from the front, occur. Near the ends of the slit, on the outer edges of the nebula, the components merge, because at these places the motion of the gas is mainly across the line of sight (Fig. 7). It was at the outer edges, too, that Duncan found the greatest displacements of the filaments in his measurements on direct photographs of M1. A simple computation, in which equivalence of motion in and across the line of sight is assumed, gave a distance to the Crab Nebula of about 5000 light years.

Now this distance of several thousand light years immediately suggested that the Crab Nebula may have originated in that very rare event, a supernova outburst. The nova observed by the Chinese evidently reached a very bright apparent magnitude; thus, if it was 5000 light years distant, it must have had an absolute magnitude far greater than ordinary novae. Lundmark, whose knowledge of astronomical literature was encyclopedic, not only pointed out, in 1938, the possibility of a supernova origin but cited a report published in 1934 by the Japanese scholar Iba (*21*), who had found in some ancient Japanese chronicles an independent record of the nova observed by the Chinese in A.D. 1054. Besides confirming the time of appearance and the position of the nova, the Japanese account contained the invaluable datum that it was as bright as Jupiter. This observation, even when no allowance is made for absorption of light in the space smog of the Milky Way, means that the old nova had an absolute magnitude of at least − 13; this clearly puts the star of A.D. 1054 in the supernova class from the standpoint of luminosity.

These findings greatly stimulated interest in the Crab Nebula as the first known remnant of one of nature's greatest explosions. For example, Oort, who was in this country in 1939, thought that a more complete search of ancient oriental records might turn up still more information. After his return to Holland, he interested his Leiden University colleague, J. J. L. Duyvendak, in the problem. Duyvendak was one of the world's leading Oriental scholars, and in only a few months of research he uncovered additional Chinese records



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DATE des OBSERVATIONS.	Numeros des Nébuleuſes	ASCENSION DROITE. En Temps. H. M. S.	ASCENSION DROITE. En Degrés. D. M. S.	DÉCLINAISON. D. M. S.	Diamètre en degrés & min. D. M.
1758. Sept. 12	1.	5. 20. 2	80. 0. 33	21. 45. 27 B	
1760. Sept. 11	2.	21. 21. 8	320. 17. 0	1. 47. 0 A	0. 4
1764. Mai. 3	3.	13. 31. 25	202. 51. 19	29. 32. 57 B	0. 3
8	4.	16. 9. 8	242. 16. 56	25. 55. 40 A	0. 2½
23	5.	15. 6. 36	226. 39. 4	2. 57. 16 B	0. 3

229 1784.

N.os des Nébul.	Détails des Nébuleuſes & des amas d'Étoiles. *Les poſitions ſont rapportées ci-contre.*
1.	Nébuleuſe au-deſſus de la corne méridionale du Taureau, ne contient aucune étoile; c'eſt une lumière blancheâtre, alongée en forme de la lumière d'une bougie, découverte en obſervant la Comète de 1758. Voyez la Carte de cette Comète, *Mém. Acad. année 1759, page 188;* obſervée par le Docteur Bévis vers 1731. Elle eſt rapportée ſur l'*Atlas céleſte* anglois.
2.	Nébuleuſe ſans étoile dans la tête du Verſeau, le centre en eſt brillant, & la lumière qui l'environne eſt ronde; elle reſſemble à la belle Nébuleuſe qui ſe trouve entre la tête & l'arc du Sagittaire, elle ſe voit très-bien avec une lunette de deux pieds, placée ſur le parallèle de α du Verſeau. M. Meſſier a rapporté cette nébuleuſe ſur la Carte de la route de la Comète obſervée en 1759. *Mém. Acad. année 1760, page 464.* M. Maraldi avoit vu cette nébuleuſe en 1746, en obſervant la Comète qui parut cette année.
3.	Nébuleuſe découverte entre le Bouvier & un des Chiens de Chaſſe d'Hévélius, elle ne contient aucune étoile, le centre en eſt brillant & ſa lumière ſe perd inſenſiblement, elle eſt ronde; par un beau ciel on peut la voir avec une lunette d'un pied: elle ſera rapportée ſur la Carte de la Comète obſervée en 1779. *Mémoires de l'Academie de la même année.* Revue le 29 Mars 1781, toujours très-belle.
4.	Amas d'étoiles très-petites; avec une foible lunette on le voit ſous la forme d'une nébuleuſe; cet amas d'étoiles eſt placé près d'*Antarès* & ſur ſon parallèle. Obſervé par M. de la Caille, & rapporté dans ſon Catalogue. Revu le 30 Janvier & le 22 Mars 1781.
5.	Belle Nébuleuſe découverte entre la Balance & le Serpent, près de l'étoile du Serpent, de ſixième grandeur, la cinquième ſuivant le Catalogue de Flamſtéed: elle ne contient aucune étoile; elle eſt ronde, & on la voit

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Fig. 2. The first page in Messier's famous catalogue of nebulae, showing the first entry, M1, which is now known as the Crab Nebula

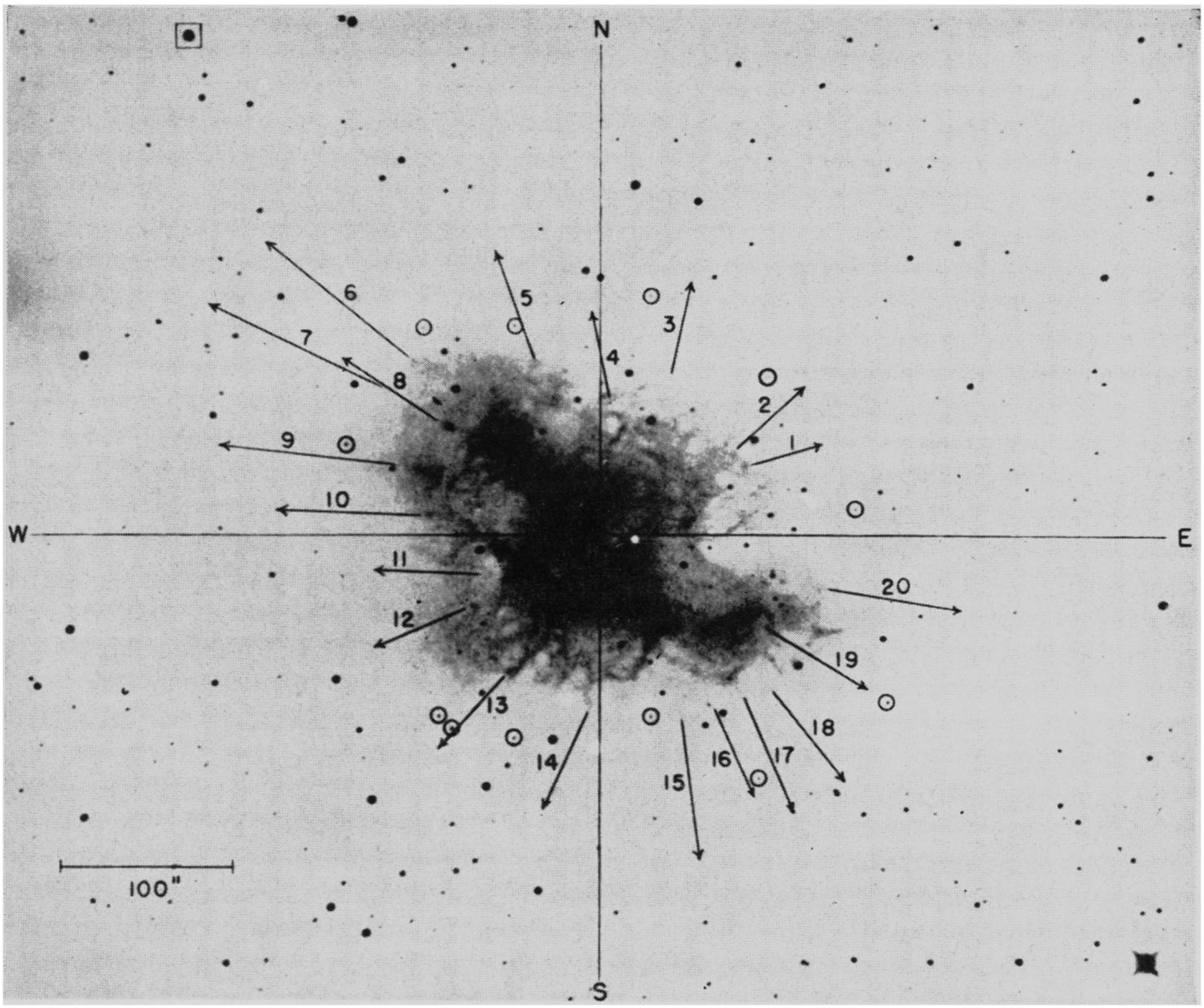


Fig. 3. Outward motions measured for some filaments in the Crab Nebula. The arrows indicate the directions and amounts for 500 years.

of the 1054 "guest star." as it was called by the polite Sons of Heaven. Duyvendak found that this object was observed at Peking and Kai-feng; that, like Venus, it was seen in daylight for 23 days; and that it was seen in the night sky for nearly 2 years.

At the time Duyvendak uncovered these records, 20 years ago, Holland had been invaded and occupied by the German army and all regular communications had ceased. Nevertheless, Oort was able to send out the new data via Sweden, and I was able to publish them, together with a detailed astronomical discussion, in 1942 (*22*). From this study it was possible to conclude with reasonable assurance not only that the Crab Nebula originated in A.D. 1054 but that the new star seen independently by the Chinese and the Japanese was one of the brightest supernovae on record: it blazed with the brilliance of 500 million suns. A brightness of this order of magnitude is difficult to comprehend; one can get some idea of it from the knowledge (from a simple calculation) that if such a supernova were at the distance of Sirius—9.5 light years—it would shine more brightly than the full moon.

It seems strange that no record of this supernova of 1054 has been found among European or Middle East chronicles. Europe, of course, was at that time in the dark ages scientifically, and there are almost no records of astronomical events in the middle of the 11th century. Although astronomy was a somewhat more flourishing study in Arabia at that time, there seems to be a hiatus in the extant records for the period around 1054, according to some scholars whom I have consulted on the subject.

But if the Old World has so far failed to yield up any records of the 1054 supernova, the New World may nevertheless have produced some. In 1955, William C. Miller (*23*), staff photographer at the Mount Wilson and Palomar Observatories, proposed a plausible astronomical interpretation of two prehistoric drawings found by him and Helmut Abt in northern Arizona (Fig. 8). One is in a cave, the other is on a canyon wall, and both occur amid Indian ruins and artifacts. Each drawing contains a crescent and circle. Because these symbols are normally rare among Indian figures, they attracted immediate attention. Miller makes a strong case for the view that the figures

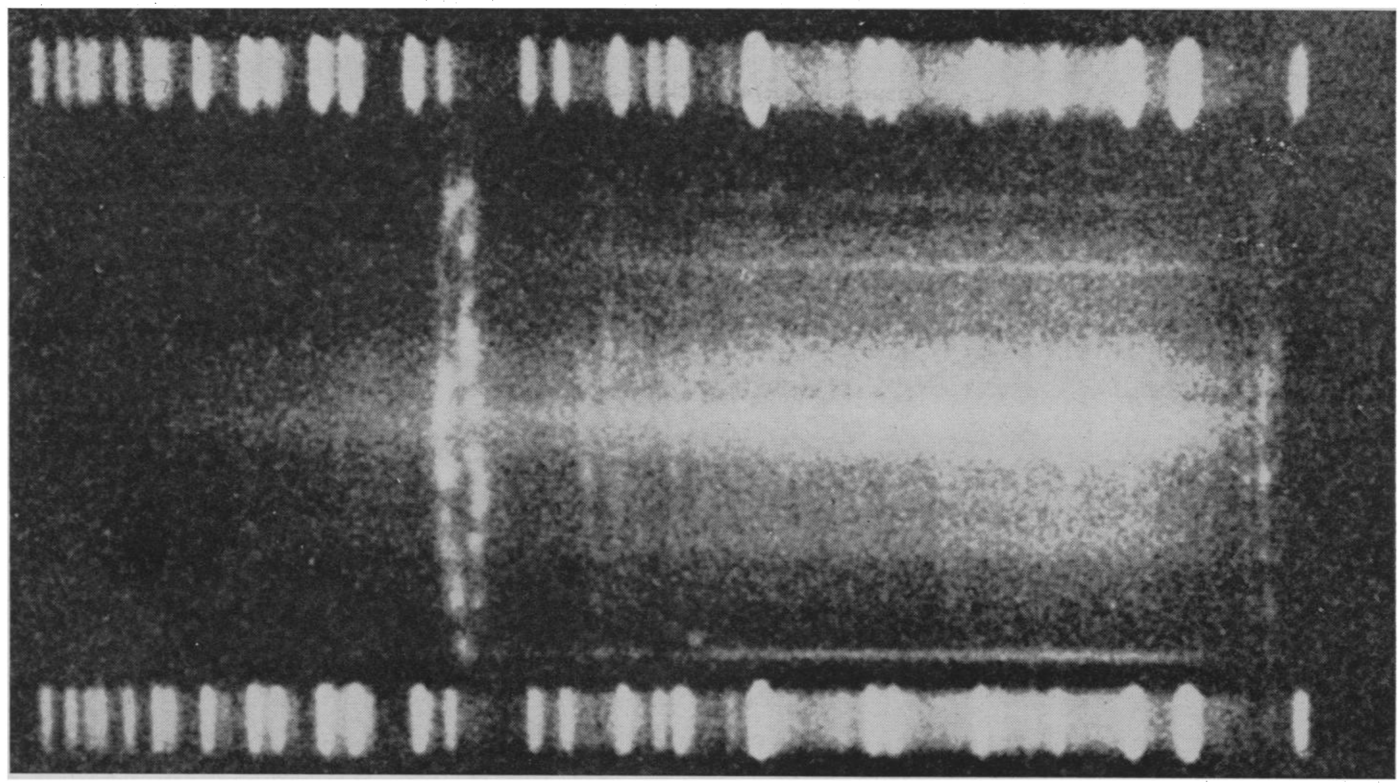


Fig. 4. Spectrum of the Crab Nebula in the ordinary photographic region. The strongest radiation, on the left, is due to ionized oxygen (3727A), the fainter lines, on the right, are due to hydrogen and doubly ionized oxygen. The bowed-line structure is due to expansion of the nebular gases.

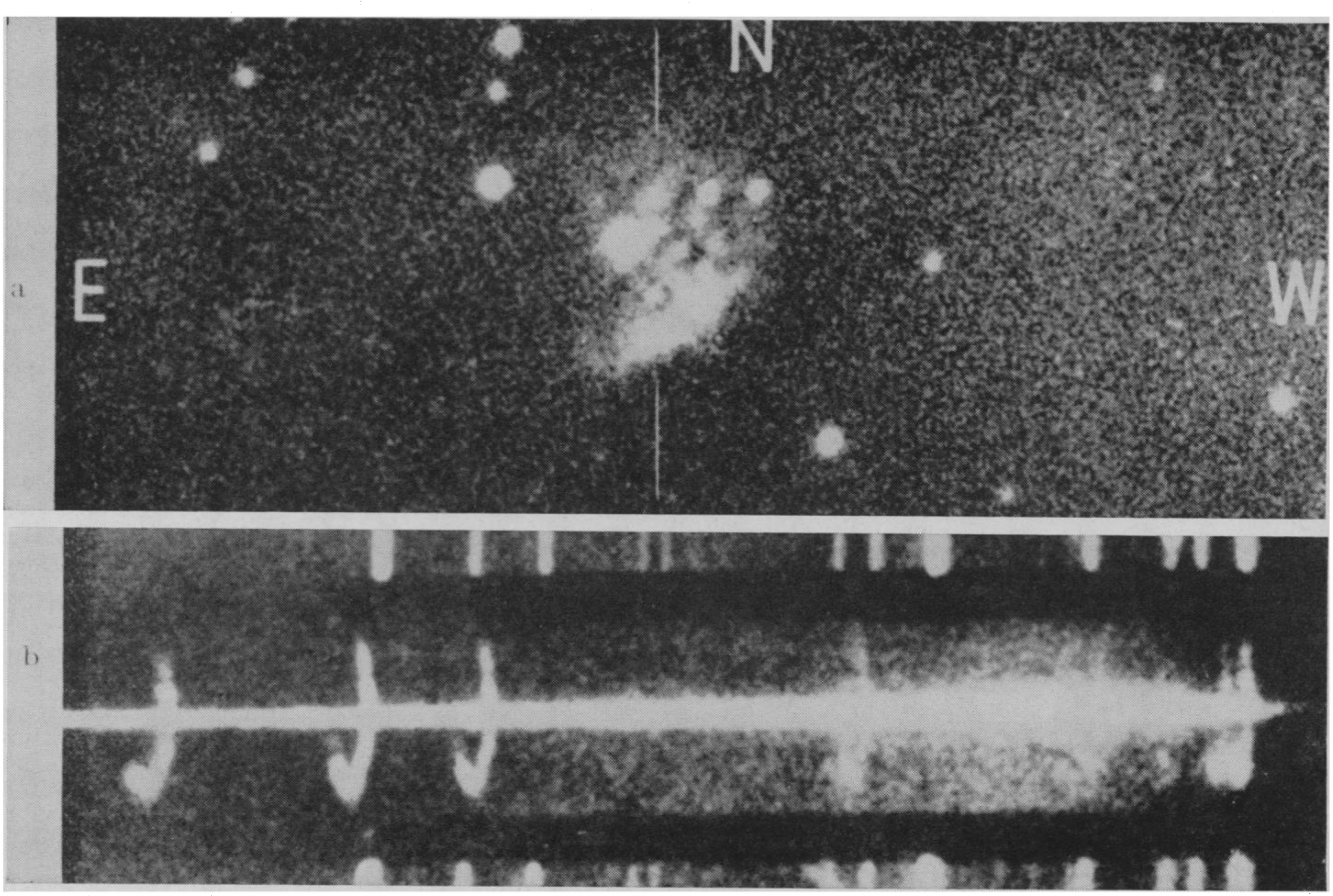


Fig. 5. Nebula and spectrum of Nova Persei (1901). The irregular distribution of the outward-moving gas gives the incomplete but bowed spectrum lines.

represent the crescent moon with a very bright star near, or just below, one cusp. By considering various alternate possibilities, which he eliminated by reasonable arguments, Miller was led to conclude that the most likely event was the 1054 supernova. He tested this interpretation in two ways: (i) by calculating the position and phase of the moon for early July, 1054, when the supernova was first seen in the Orient, and (ii) by asking anthropologists to investigate the probability of Indian occupation of the sites at the time in question. The results of these studies supported his intrepretation. On the morning of 5 July 1054, just before dawn, the moon was 2 degrees north of the position of the Crab Nebula, and potsherds collected at the two Arizona sites indicate Indian occupation between A.D. 900 and 1100. The evidence is circumstantial, but, so far as it goes, there are no inconsistencies. Miller's imaginative treatment of an old subject could, therefore, represent still another piece in the Chinese puzzle of 1054.

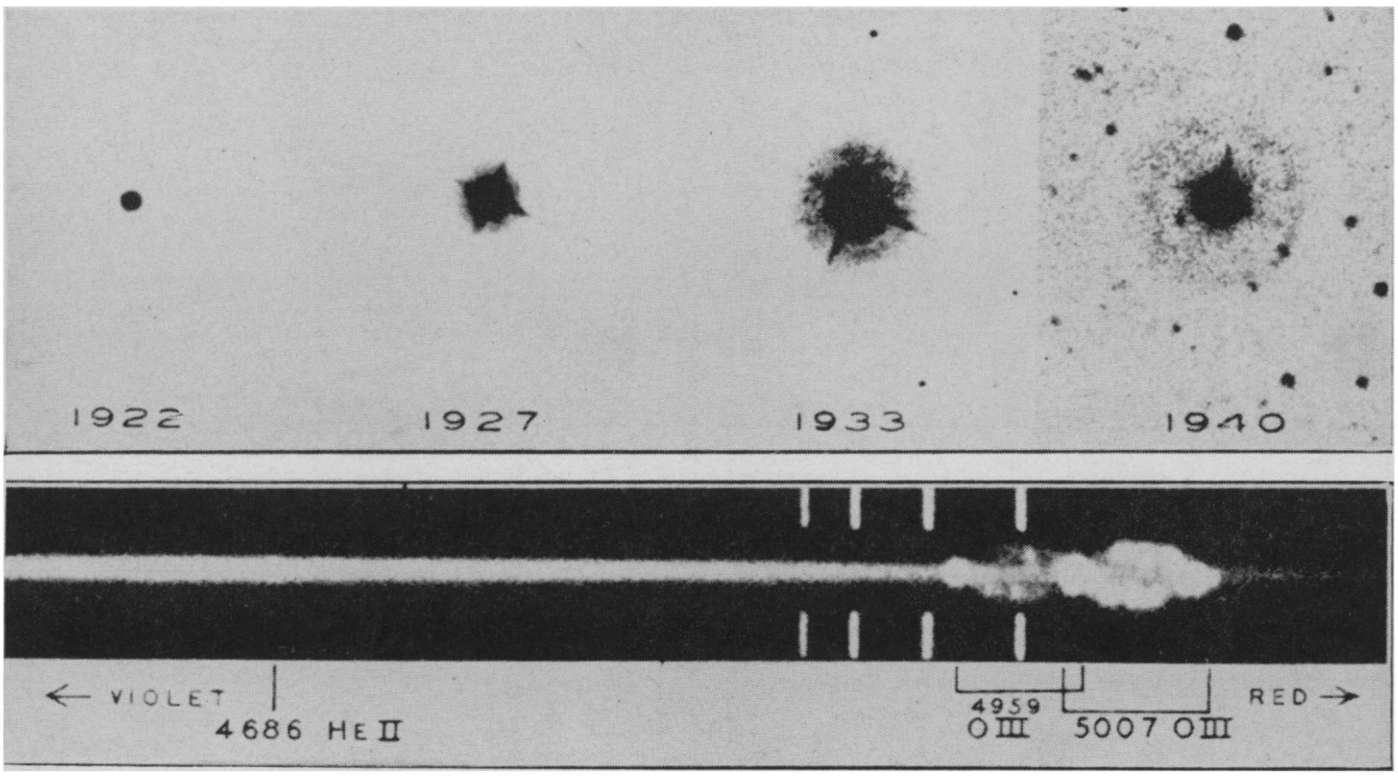
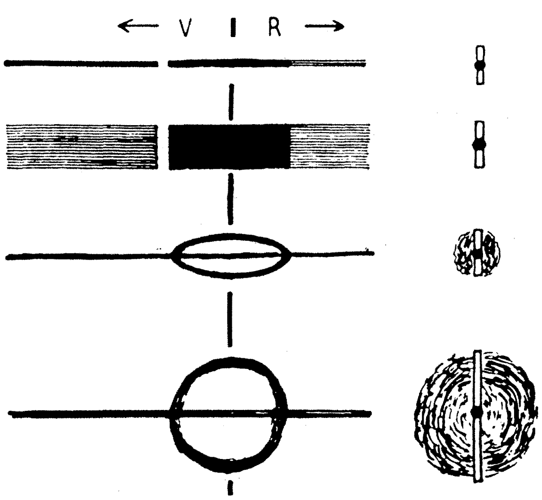


Fig. 6. Nebula and spectrum of Nova Aquilae (1918). This expanding nebula was much closer to the star, so the spectrum lines are very short, with most of the bowing along the spectrum instead of perpendicular to it.



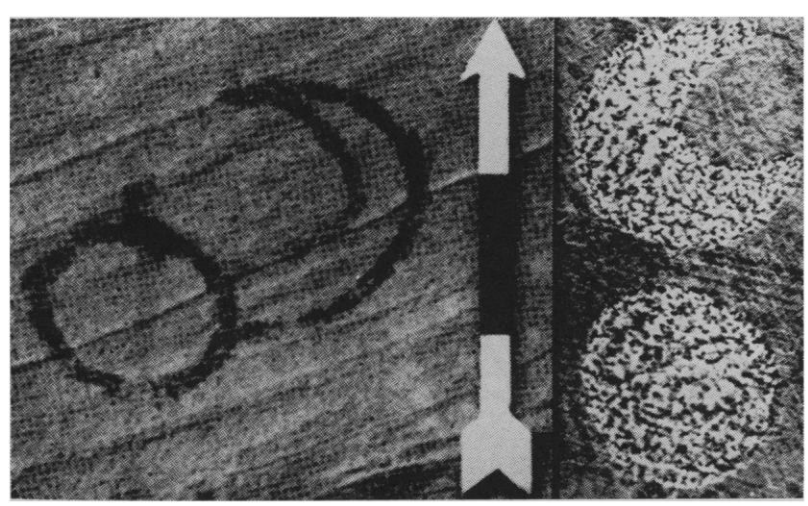


Fig. 7 (left). Schematic drawings to explain the formation of bowed spectrum lines from a gaseous nebula expanding around a nova. The spectrum in Fig. 6 for Nova Aquilae (1918) corresponds to the conditions in the third spectrum of the diagram; the spectra in Figs. 4 and 5, for the Crab Nebula and Nova Persei (1901), correspond to an extension of the sequence to several more stages beyond the lowest spectrum drawn. Fig. 8 (right). Prehistoric Indian drawings found in a cave and on a canyon wall in northern Arizona. The crescent and circle have been interpreted as the crescent moon near the supernova of A.D. 1054, which produced the Crab Nebula.

Studies of the Nebular Gases

As soon as Duyvendak's new data became available and the supernova origin of the Crab Nebula seemed certain, Baade and Minkowski used the Mount Wilson Observatory's 100-inch reflector for a detailed study of the expansion, composition, and excitation of the nebular gases. Baade (*24*) photographed the nebula under critical seeing conditions with various color filters (Fig. 9) and established the highly significant fact that its radiation is from sources of two kinds: a network of filaments, which is expanding and gives an emission spectrum of lines of oxygen, hydrogen, helium, neon, and sulfur, and an amorphous mass of gaseous material which has a strong continuous spectrum without detectable absorption lines.

Minkowski (*25*) investigated the source of energy and the physical constitution of the nebula by obtaining better spectrograms of the nebulosity and of what seemed to be the central, exciting star. In the middle of the nebula there are two 16th-magnitude stars, and from the fact that one of them shows no measurable proper motion and has a spectrum with no perceptible lines, it was reasonable to assume that this star is the post-supernova, fainter than at maximum in 1054 by some 20 magnitudes. From a theoretical analysis, Minkowski found that the continuous nebular radiation probably comes from electrons in a highly ionized gas that has a density of 1000 electrons per cubic centimeter and a temperature of 50,000°, and that the central star is 1/50 the diameter of the sun and 30,000 times as bright, with a temperature of 500,000°. Needless to say, these properties of the central star, if correct, indicate that in the final stage of a supernova matter is in a highly degenerate state.

Up to this point we have considered what was known or conjectured about the Crab Nebula before World War II. Although it hardly seemed possible that still more exciting results about it could emerge, that is precisely what has happened. I shall briefly review these events.

Radio Techniques

One of the really revolutionary advances in astronomy in our times occurred when radio techniques, developed during the war, were applied to astronomical sources. The first surveys in the radio wavelength region were made with modest-sized radio telescopes that detected only the brighter celestial radio

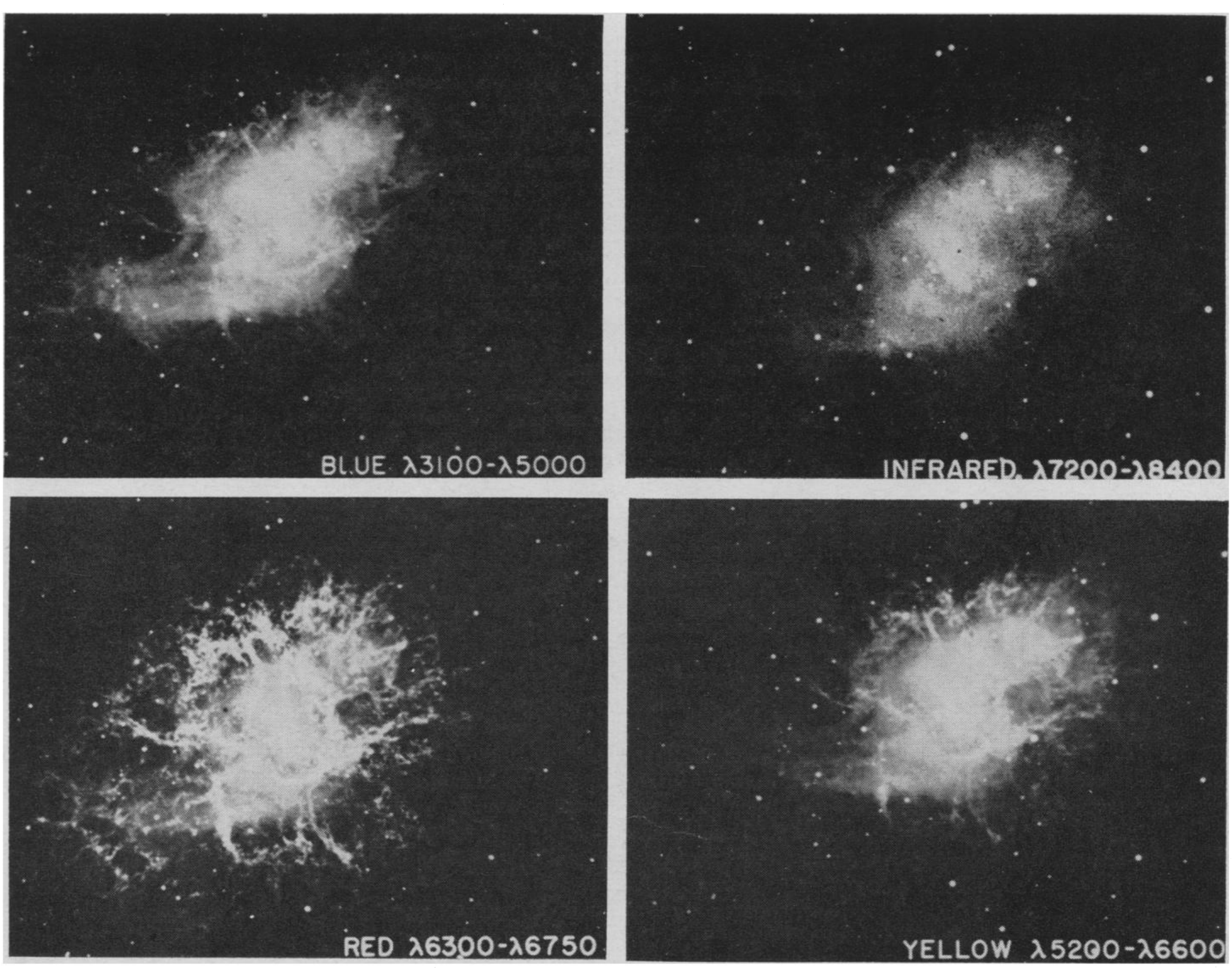


Fig. 9. Baade's photographs of the Crab Nebula in four wave-length regions, made with the 100-inch telescope. These show the separation of the light into a filamentary system and an amorphous mass.

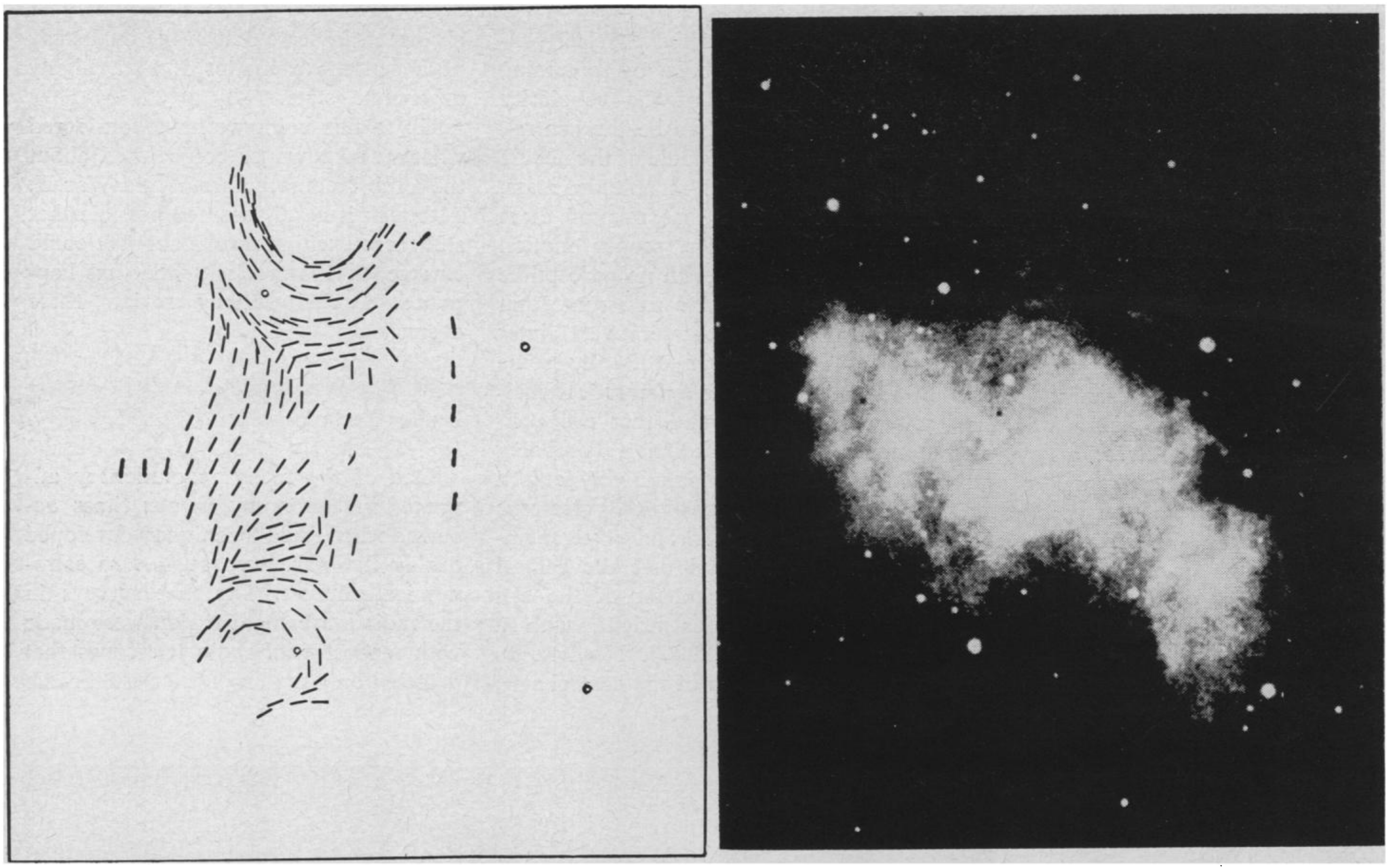


Fig. 10. Polarization measurements for some points in the Crab Nebula. The patterns on two sides of the nebula show a radial relationship to two "dark bays" in the nebulosity.

sources. Also, these instruments yielded positions of low accuracy, until interferometric methods were developed. During this pioneering phase, however, it soon became evident that one of the strongest radio sources is in Taurus; depending on the radio wavelength used, this source ranked either third or fourth in the whole sky. Moreover, identification of even the strongest radio sources with optical resources at first proved difficult, because, with one exception, the optical objects were extremely faint. The exception was the Crab Nebula, one of the first radio sources to be identified. This identification, made by Bolton, Stanley, and Slee in 1949 (*26*), also showed the Crab Nebula to be unique, relatively bright at *both* radio and optical wavelengths. The strength of its radio radiation is indicated by the fact that the nebula emits in the radio region 100 times more energy than the sun emits in all wavelengths.

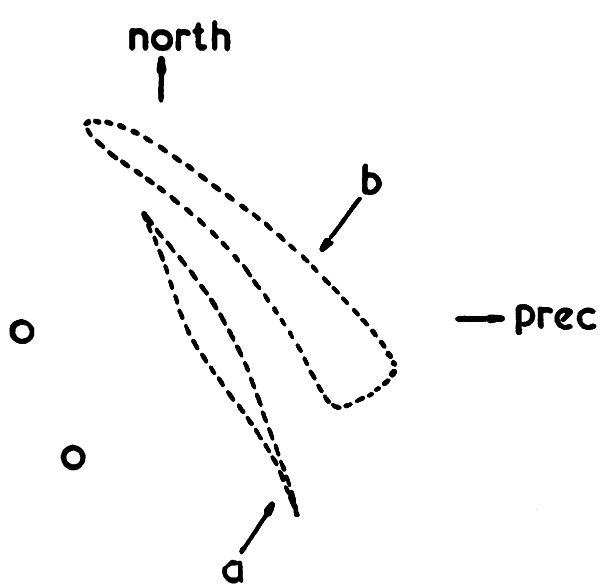


Fig. 11. Schematic diagram of "light ripples" observed near the center of the Crab Nebula. The phenomenon is an arclike feature (*a*), which appears near the double star at left and moves in a few weeks toward the fixed feature (*b*), at right, where it fades to invisibility.

The strong radio radiation from the Crab Nebula made it necessary to reexamine the mechanism of energy production in the nebula. In a thermal process, implausibly high black-body, or thermal, temperatures (temperatures of half a million degrees) would be required in the nebular gas, to yield the strong radio emission. Thus some other, nonthermal process had to be sought, and one was suggested in 1953 by the Russian astrophysicist Shklovsky (*27*). He proposed that the Crab Nebula's strong continuous radiation might come from electrons being accelerated in a magnetic field, such as had been theoretically and observationally studied in particle accelerators such as synchrotons. Since this "synchroton radiation" is polarized, Shklovsky predicted that the optical continuous emission of the Crab Nebula may also be polarized. The Russian astronomers Vashakidze (*28*) and Dombrovsky (*29*), of the Burakan Observatory, soon confirmed this prediction, and their work stimulated further and much more detailed in-

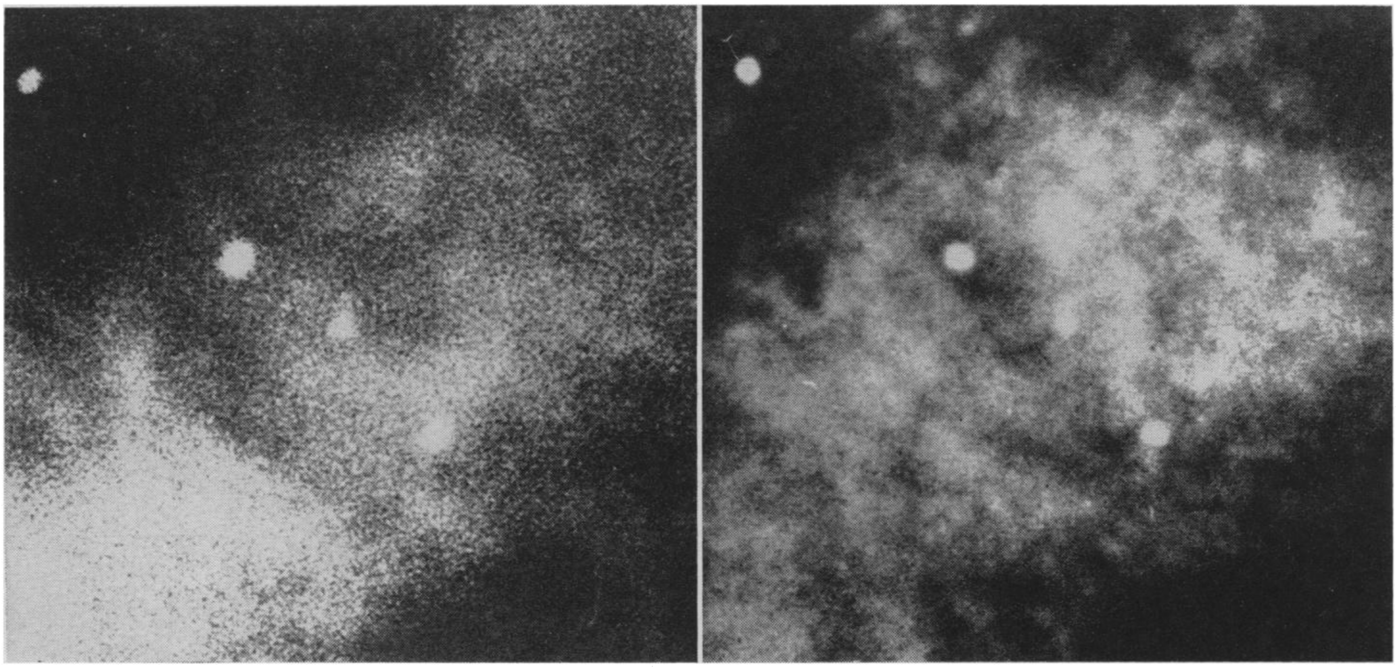


Fig. 12. Slower changes in brightness observed in a region of the Crab Nebula. The photographs were taken with the 100-inch telescope on 19 November 1924 (left) and on 25 October 1938 (right).

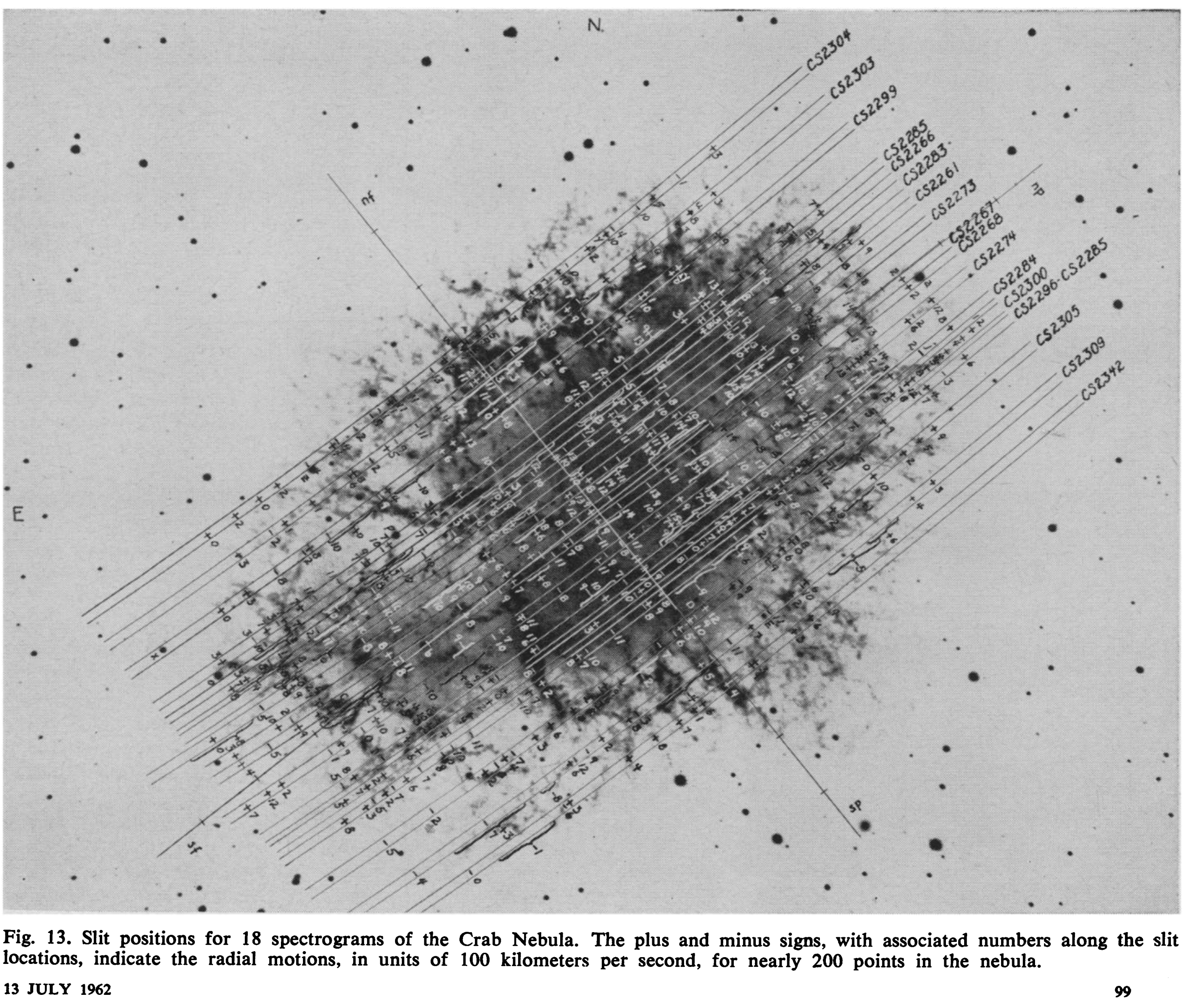


Fig. 13. Slit positions for 18 spectrograms of the Crab Nebula. The plus and minus signs, with associated numbers along the slit locations, indicate the radial motions, in units of 100 kilometers per second, for nearly 200 points in the nebula.

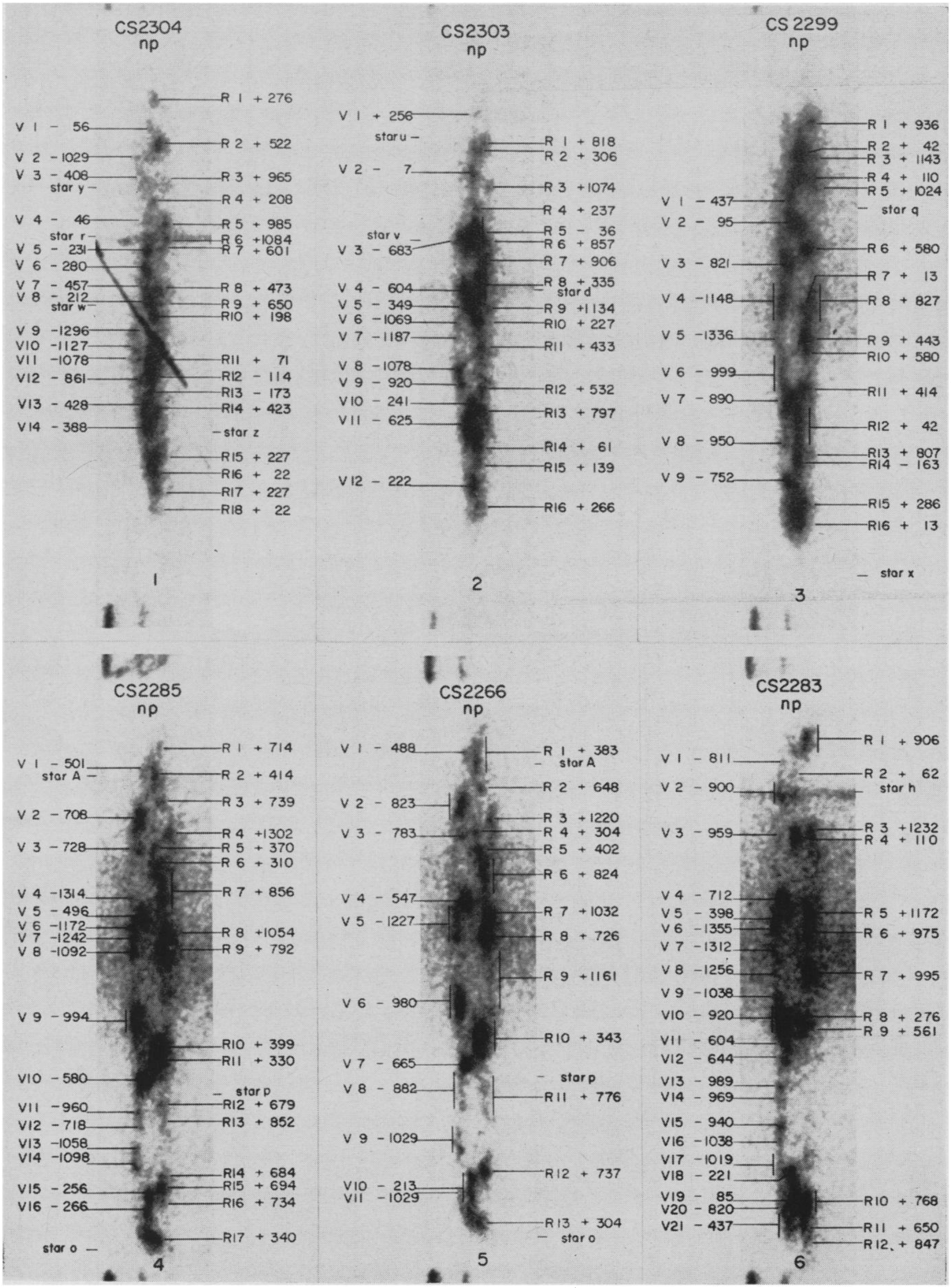


Fig. 14. Radial velocities measured for the radiation at 3727A for six slit positions in the Crab Nebula. From upper left (the inclined dark line is a defect) to lower right the emission line gradually becomes doubled, as the gas motions change from *across* the line of sight to *in* the line of sight. The numbers are radial velocities (in kilometers per second)—plus for recession, minus for approach. The *CS* plate numbers correspond to the slit positions in Fig. 13.

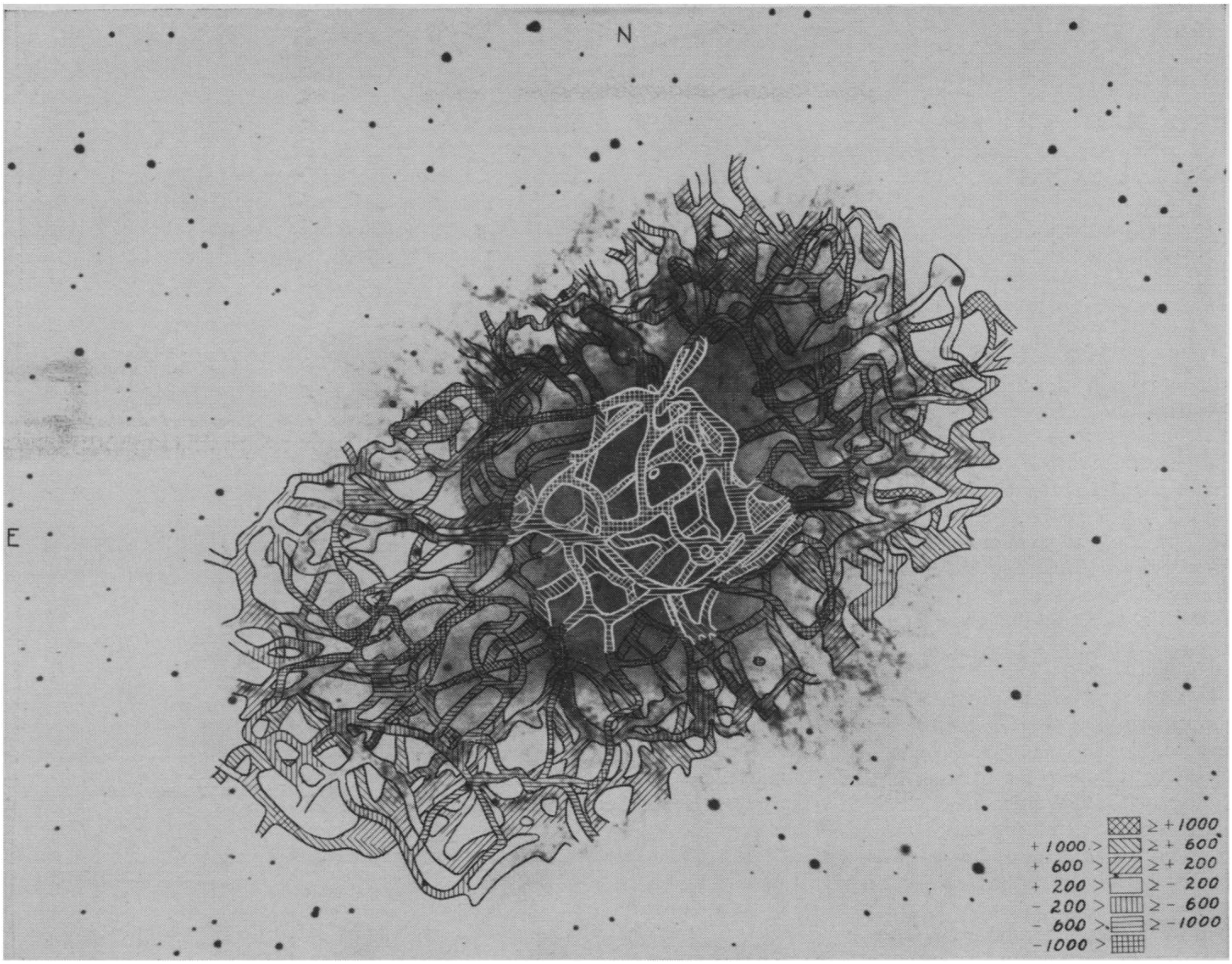


Fig. 15. A velocity-spatial representation of the filamentary system of the Crab Nebula. On certain assumptions, the radial velocities may indicate how the filaments coil around from the front to the back of the nebula, giving some indication of its spatial structure. The key at lower right gives the ranges (in kilometers per second) for the seven radial-velocity intervals used in drawing the diagram.

vestigations elsewhere, particularly by Oort, Walraven, and Woltjer (*30*) in Holland and by Baade (*31*) and Greenstein and Minkowski (*32*) in this country.

On the basis of the theory of synchroton radiation, the Dutch astronomers calculated the energies of the electrons and the strength of the magnetic field required to yield the radiation in the optical and radio wavelength regions. As it turns out, it is easy to account for the radio emission but not for the optical. In the radio range, electrons with energies of about 100 Mev are required, but in the optical range electron energies have to be about 200 Bev, ten times greater than any yet produced in a terrestrial particle accelerator. Energies of this order are characteristic of cosmic rays, and this result for the Crab Nebula has suggested that supernova outbursts may be one of the principal producers of cosmic rays (*33*). The calculated magnetic field strength of about 1/1000 gauss, on the other hand, is not at all remarkable, although, as Woltjer has remarked, its origin poses one of the most difficult problems.

Observational Techniques

On the observational side, Baade's photographs taken with the 200-inch telescope yielded, as usual, highly significant results. His photographs in polarized light enabled Woltjer to make a detailed analysis of the structure of the magnetic field of the Crab Nebula. For this purpose Woltjer used the theory of force-free magnetic fields, which predicts that the boundary of such a field has no radial component and that the field is surrounded by a surface current. Precisely these effects are shown in the pattern of polarization over the nebula, particularly at some of the "dark bays" on the edges (Fig. 10), where the inferred circular lines of force around a current-carrying filament prevent electrons from entering. Since the filaments appear to form a net around the whole nebula, their identification with a surface current around the inner force-free field seems plausible, according to Woltjer.

Baade had discovered earlier, on 100-inch reflector plates, some remarkable "light ripples" near the center of the nebula. Because of their obvious bearing on the mechanism by which the nebula continually receives large amounts of energy, these observations are of great importance. The phenomenon requires much more extensive study, but Baade, before he died, determined that these ripples occur somewhat irregularly, about three times a year, that they move with a speed that may be a considerable fraction (1/10) of the velocity of light, and that they disappear a short distance out from the central star (Fig. 11). Piddington (*34*) has interpreted these ripples as being hydromagnetic waves traveling through a tenuous medium and suggests that it is their energy that accelerates the electrons to produce the continuous emission.

Details of the most recent developments in observational study of the Crab Nebula have not yet been published. The first of these developments is a photometric study of slower and larger-scale changes in intensity over the nebula as a whole, undertaken by Woltjer. He has mentioned, in a preliminary way, that locally, these intensity changes may amount to 50 percent (Fig. 12), and that the continuous radiation consists of two parts: a more amorphous part, showing little variation with time, and a number of concentrations that appear to be superimposed in the amorphous part and to move through the nebula in the course of time. Woltjer concludes that these luminous, moving concentrations probably should also be considered hydromagnetic waves, but waves on a far larger scale than Baade's light ripples near the center. If he is correct, their occurrence may indicate that there are sometimes periods of several years when the activity of the central star is unusually violent.

The second new development is a series of 18 narrow-slit spectrograms covering nearly the whole nebula (Fig. 13), which I obtained with the Crossley nebular spectrograph. I took these with the aim of measuring radial velocities, from λ3727 [OII], for about 200 points in the nebula (Fig. 14). Then, on the assumption that each such point is located in space by its radial velocity, and by its rectangular coordinates with respect to the center of the nebula, a spatial model of the filaments could be constructed. The result indicates that the network of filaments for which radial velocities were measured consists, on the whole, of a distorted ellipsoidal shell, somewhat pear-shaped (Fig. 15), but with parts of some filaments near the center apparently inside the shell. Walraven, who has studied a smaller series of wide-slit spectra from a similar point of view, has aptly described this result as follows: "The actual situation is more likely to be that of a single shell which is not spherical but has the shape of a bag, or net of fine thin filaments, which is filled with a fluffy material—the cloud of electrons—and heavily tied in with ropes—the strong filaments. Between the ropes the thin net bulges outward by the pressure of the fluffy material."

Woltjer, who has made by far the most comprehensive study of the Crab Nebula (*35*), has pointed out a curious property of the various models used in calculating the continuous emission of the Crab Nebula. All the models predict a difference in color index between the center and edges of the nebula, in the sense that the outer parts should be redder by 0.35 magnitude. Walraven's photoelectric color observations, however, indicate that the outer parts are bluer (possibly because of the influence of the stronger blue and ultraviolet emission lines). Woltjer therefore concluded that the models used cannot be correct. However, a color photograph taken with the 200-inch telescope shows both colors around the edges: a red border inside a blue one!

Other Hypotheses

On this note of uncertainty we leave the Crab Nebula. Despite what has been learned, if history is any guide it is fair to say that we are a long way from knowing all its secrets. For example, possibilities other than hydromagnetic waves have been suggested to explain the production of the high-energy electrons. Geoffrey Burbidge (*36*) has suggested that these electrons may be continually produced by a primary beam of protons, of greater energy, that collide with the gas atoms and produce unstable particles, which in turn decay and yield high-energy electrons. Still another, more speculative possibility is mentioned by Burbidge and Hoyle (*37*): that the interstellar gas in the Galaxy, which may pervade the space occupied by the Crab Nebula, contains antimatter. Even if such antimatter were present only to the extent of one part in ten million, collisions of protons in the nebula with antiprotons in the interstellar gas would produce enough energy to give the observed radio emission. Such high-powered hypotheses (if they are valid), the exciting star (if there is one), the amorphous cloud of electrons (if it exists), and the filamentary system of gases carrying current and a magnetic field (if they do)—all these aspects of the Crab Nebula call to mind Winston Churchill's famous phrase, "a riddle, wrapped in a mystery, inside an enigma" (*38*).

References and Notes

1. Hutton, Shaw, Pearson, *Abr. Phil. Trans. Roy. Soc. (London)* **8**, 117 (1809).
2. B. Brown, *Astronomical Atlases, Maps and Charts* (Search, London, 1932), pp. 51, 57–58.
3. C. Messier, *Mem. Roy. Acad. Sci.* (1759), pp. 165 and 188, text and map, respectively.
4. J. F. Lalande, *Astronomie* (Paris, ed. 3, 1792), vol. 1, p. 242.
5. C. Messier, *Mem. Roy. Acad. Sci.* (1771), p. 435 (First List).
6. W. Herschel, *Phil. Trans. Roy. Soc. (London)* (1818), p. 435; J. Herschel, *ibid.* (1883), p. 503.
7. Rosse, *Phil. Trans. Roy. Soc. (London)* (1844), p. 322.
8. W. Lassell, *Mem. Roy. Astron. Soc.* **23**, 53 (1854).
9. I. Roberts, *Photographs of Stars, Star Clusters and Nebulae*, vol. 1 (1893), p. 53; vol. 2 (1899), p. 169.
10. C. O. Lampland, *Publs. Astron. Soc. Pacific* **33**, 79 (1921); *Harvard Bull. No. 743* (1921).
11. J. C. Duncan, *Proc. Natl. Acad. Sci. U.S.* **7**, 179 (1921); *Mt. Wilson Observatory Communs. No. 76* A later, more extensive, set of expansion measurements is given in *Astrophys. J.* **89**, 482 (1939); *Contribs. Mt. Wilson Observatory No. 609.*
12. E. E. Barnard, *Astron. J.* **30**, 86 (1917); *Astrophys. J.* **49**, 199 (199).
13. K. Lundmark, *Publs. Astron. Soc. Pacific* **33**, 225 (1921).
14. ———, *Festskr. Tillägnad Osten Bergstrand* (Uppsala, 1938), p. 97.
15. V. M. Slipher, *Harvard Bull. No. 743* (1921).
16. R. F. Sanford, *Publs. Astron. Soc. Pacific* **31**, 108 (1919).
17. E. Hubble, *Astron. Soc. Pacific Leaflet No. 14* (1928).
18. N. U. Mayall, *Publs. Astron. Soc. Pacific* **49**, 101 (1937).
19. D. B. McLaughlin, *Sky and Telescope* **5**, No. 554 (1946).
20. M. L. Humason, *Publs. Astron. Soc. Pacific* **46**, 229 (1934).
21. Y. Iba, *Popular Astron.* **42**, 243 (1934).
22. J. J. Duyvendak, N. U. Mayall, J. H. Oort, *Publs. Astron. Soc. Pacific* **54**, 91 (1942).
23. W. C. Miller, *Astron. Soc. Pacific Leaflet No. 314* (1955).
24. W. Baade, *Astrophys. J.* **96**, 188 (1942); *Contribs. Mt. Wilson Observatory No. 665.*
25. R. Minkowski, *Astrophys. J.* **96**, 199 (1942); *Contribs. Mt. Wilson Observatory No. 666.*
26. J. G. Bolton, G. J. Stanley, O. B. Slee, *Nature* **164**, 101 (1949).
27. I. S. Shklovsky, *Doklady Akad. Nauk S.S.S.R.* **90**, 983 (1953).
28. M. A. Vashakidze, *Astron. Tsirk. No. 147* (1954).
29. V. A. Dombrovsky, *Doklady Akad. Nauk S.S.S.R.* **94**, 1021 (1954).
30. J. H. Oort and T. Walraven, *Bull. Astron. Inst. Neth.* **12**, 285 (1956); T. Walraven, *ibid.* **13**, 293 (1957); L. Woltjer, *ibid.* **14**, 39 (1957).
31. W. Baade, *ibid.* **12**, 312 (1956).
32. J. L. Greenstein and R. Minkowski, *Astrophys. J.* **118**, 1 (1953).
33. M. M. Shapiro, *Science* **135**, 175 (1962); many references are given to previous work.
34. J. H. Piddington, *Nature* **176**, 875 (1955).
35. L. Woltjer, dissertation (1957).
36. G. R. Burbidge, *Astrophys. J.* **127**, 48 (1958).
37. ———, and F. Hoyle, *Nuovo Cimento* **4**, 558 (1956).
38. This is contribution No. 16 from the Kitt Peak National Observatory.