SESSION 4

RELATION OF CRAB NEBULA TO OTHER SUPERNOVA REMNANTS

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4.1 COMMENTS ON SUPERNOVA REMNANTS AND ANCIENT NOVAE

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Abstract. The low expansion velocity of the Crab Nebula proves conclusively that the supernova of +1054 was not type I. Only five supernova remnants found in radio surveys are connected with ancient novae, +185, +1006, +1054, +1572, +1604. This corresponds to reasonable expectation. Most of the objects in historical records were comets, the remainder mostly ordinary novae. Most radio remnants are too old, some too heavily obscured to be found in historical records.

It seems unnecessary to recite here all the properties of the Crab Nebula which make it unique. It differs in every respect from all other supernova remnants. It is not surprising to find that the supernova of +1054, whose remnant is the Crab Nebula, was not one of the two most frequent types of supernovae.

The supernova of +1054 was considered for a long time as a supernova of type I. This assignment came about because it was not known that there is more than one type of supernova when Mayall and Oort (1942) showed that the available evidence was consistent with the interpretation that the nova of +1054 was a supernova and that the Crab Nebula is its remnant. The information available at that time seemed to show that the supernova of +1054 was similar to the supernova in IC 4182. This supernova later became the prototype of the supernova of type I, and this type was then assigned to the supernova of +1054. This classification can no longer be maintained (Minkowski, 1966, 1968).

All we know about the lightcurve of the supernova of +1054 is that it ceased to be visible in daytime at +23 days, and was no longer visible at +653 days. This indicates a decline of 8.5 mag., possibly less, between +23 and +653 days.

No other supernova has been observed for as long a period as that of +1054. Kepler's nova was observed to +356 days, Tycho's nova to +457 days, the supernova in IC 4182 to +635 days photographically, but visually only to +100 days. Extrapolation leads to a decay between +23 and +653 days of 11.3 mag. for Tycho's nova, 11.0 mag. for Kepler's nova, and 10.6 mag. for the supernova in IC 4182 (on the assumption that the color did not change after +100 days). The close agreement of these values demonstrates, of course, the well known similarity of the light curves which leads to the classification of Tycho's and Kepler's nova as supernovae of type I. There is a difference of 2.5 mag. between the decay of the supernova of +1054 and of the supernovae of type I. In view of many uncertainties, this is not quite conclusive. It tends to contradict the classification of the supernova of +1054 as type I, but does not rule it out entirely. A classification as type II can safely be ruled out; these supernovae show a much more rapid decline after the initial period.

The best argument against the classification of the supernova of +1054 as type I

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is furnished by the low velocity of expansion of the Crab Nebula. Unfortunately the Crab Nebula is a very irregular object. This causes difficulties for precise determinations of the velocity of expansion and of the distance. Trimble (1968) estimates $+1450$ km sec^{-1} as the velocity of expansion in the centre of the nebula. If the roughly elliptical nebula is prolate, the velocity in the direction of the major axis is 2175 km sec^{-1} and the distance 2.0 kpc. These values are too large (Minkowski, 1970; Woltjer, 1970). A velocity of 1800 km sec^{-1} in the direction of the major axis and a distance of 1.7 ± 0.3 kpc are probably the best values. There is evidence that the expansion may be slightly accelerated, but no evidence that it might be decelerated. The absence of deceleration is not surprising because the mass of interstellar matter swept up by the nebula is not more than a few percent of the mass of the nebula. The present velocity of expansion cannot differ much from the initial value. This is quite different from the conditions in the remnant of a supernova of type I such as Tycho's nova where the average velocity – the ratio of diameter to age – is 13000 km sec^{-1}. The accreted interstellar mass in this remnant may be larger than the original mass. There may have been strong deceleration. The initial velocity may have been much higher, perhaps of the order of 20000 km sec^{-1} which would agree well with the appearance of the spectra of supernovae of type I near maximum. Supernovae of type II show velocities of the order 6000 km sec^{-1} by the widths of emission bands and in some cases by the presence of absorptions at the violet edge of the emission bands. The low velocity of expansion of the Crab Nebula shows conclusively that the supernova of +1054 was neither a supernova of type I nor an average supernova of type II. It must be one of the small fraction – about 10 per cent – of peculiar supernovae that Zwicky designates as type III, IV, and V. This conclusion agrees well with the unique properties of the Crab Nebula.

It cannot be assumed, however, that the Crab Nebula is so rare that it is the only object of its kind in the Galaxy. In particular, it seems unbelievable that there should be no observable objects of the same kind as the Crab Nebula but older. The search for such objects or sources is an interesting and important problem that can be approached in different ways.

A search for a nebula is not an efficient way to attack the problem. The probability is quite high that heavy obscuration may hide a nebula that is close to the galactic plane.

The search for a radio source is much more effective. A radio source identical to the Crab but at a distance of 10 kpc would be the 45th source in order of flux density in the 3CR catalogue, with an apparent diameter less than 1 arc min and the unusual spectral index -0.26. No such source is in the 3CR catalogue. At 20 kpc it would still be above the limit of the 3CR catalogue. The angular diameter would be less than 30 arc seconds. Such a source might be considered as extragalactic, but the spectral index would draw attention to it. No source closely similar to the Crab Nebula is in the 3CR catalogue.

If we search for older analogues to the Crab, we must ask how such objects are likely to look. The Crab Nebula is not a shell source like the 4 other sources that are

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remnants of known supernovae – +185; +1006; +1572; +1604 – and Cas A, a remnant of a relatively recent, but unobserved supernova. If the absence of the shell structure in the Crab is connected with the fact that the accreted mass and the deceleration are small, the Crab might transform itself into a shell source in the future, say during the next 10000 years. It seems likely that the shape and structure of very old remnants depends more on the conditions in the ambient interstellar medium than on conditions of the original explosion. It might be very difficult to recognize very old analogues of the Crab. But one would expect that the transformation is slow and that there are sources older than the Crab which can still be recognized as similar. 3C58 is probably a source of this kind. It is not a shell source; its brightness distribution has a central peak. There is polarization, high in some areas (Weiler and Seielstad, 1970). The spectrum is not well determined; it might not follow a simple power law. Above 700 MHz the spectral index has a small negative value. All this shows great similarity to the Crab nebula. The angular diameters are similar, but around 1000 MHz the flux density of 3C58 is about 25 times lower. This is what one would expect for a source which is older and more distant by factors of the order two, but otherwise similar to the Crab nebula. Other such sources should be observable. MSH 15−*56* might be an example. The investigation of such sources deserves more attention.

A third approach to the problem of finding analogues to the Crab is to identify remnants with ancient objects reported in the Annals of China, Japan, Korea and other historical records. This approach suffers from the same restriction as the optical search for nebulae: if the interstellar obscuration is heavy, neither the nebula nor its parent supernova can be seen. But many remnants are optically nebulosities of very low surface brightness and unobservable for this reason. In such cases the identification with an ancient supernova can confirm that a radio source is a supernova remnant and establishes its age. Five objects have been identified with ancient supernovae of +185, +1006, +1054, +1572 and +1604. They are all listed in the Annals. For the supernova of +1006 Arabic and European sources (Goldstein, 1965) add much evidence to that to be found in Oriental records (Goldstein and Ho, 1965). The supernova of +1572 is Tycho's, that of 1604 Kepler's. Korean sources give information on the light curve of Kepler's nova (Xi and Bo, 1965; Chu, 1968). The type of the supernova of +185 is doubtful. The supernova of +1006 was probably type I, Tycho's and Kepler's novae undoubtedly type I (Minkowski, 1968).

Compilations of the ancient data have been given by Hsi (1955), Ho (1962) and Xi and Bo (1965). Ho's listing is most complete and least influenced by suggested identifications of ancient objects with radio sources. Korean information has been collected recently by Chu (1968). These authors also give some information that is vital if misinterpretations are to be avoided. I will briefly summarize some important points and add some remarks on points that have been overlooked. To make a valid identification, it is not sufficient to pick out of one of these lists an object that might be in the proper position and that at a glance seems to be a supernova.

Chinese medieval astronomers recognized 21 different kinds of 'ominous' stars. The three classes which are most frequent and of most interest here are comets with tails ('hui'), comets without tails ('po'), and "guest stars" which include novae and supernovae. These designations, however, do not always define the true nature of the object. Sometimes different authors seem to quote different texts of the same record. Ho, for instance, quotes a record which designates Tycho's nova as 'hui'; other records quoted by Hsi, by Ho, and by Xi and Bo, call it a 'guest star'. A small comet without tail might easily be mistaken for a guest star. If a "guest star" is described as moving, it must have been a comet. Xi and Bo, however, give a record, which (at least in the NASA translation) states that Kepler's nova 'wandered about'. This might refer to no more than that the object was in the southwest in the beginning and in the southeast after the conjunction with the sun, as clearly stated in another record quoted by Hsi and by Xi and Bo. But if there would be no other evidence, this object might be rejected as a nova. If changes of position with time are clearly stated there can be no doubt that the object was a comet, no matter what its designation is. There are very rarely useful data on the brightness. Statements on color may sometimes refer to the true color, but colors have astrological significance (Needham, 1959). Positions are not very accurate, sometimes unreliable. Remember, for instance, that the position for the supernova of +1054 is given as southeast of ζ Tau, but the Crab Nebula is northwest of that star; one record puts it into the Pleiades (Duyvendak, 1942). One important point is that the Chinese astronomers used equatorial coordinates exclusively (Needham, 1959). Thus, an object described as having been below some star, was south of it, not at a lower altitude, a statement that would be useless unless the time of observation was stated.

Sometimes the period of visibility is stated. This is valuable information, but to use it properly we must know the brightness at which novae were discovered. This can be estimated roughly in the following way. Ho's catalog shows about 5 objects per century that were not clearly recognizable as comets. That is the same rate at which ordinary novae brighter than 0.5 mag. have occurred between 1900 and 1950. If the discovery brightness for ancient novae were much fainter than 0.5 mag., all ancient novae should be ordinary novae! If the discovery magnitude is about +0.5 mag., a supernova discovered at maximum must remain visible for at least about 200 days if it was type I, about 80 days or more if it was type II. Objects that were visible for much shorter periods cannot have been supernovae. Some may have been comets, but some must have been ordinary novae. It should not be forgotten that some ordinary novae have remained visible for more than 200 days – for instance N Aqu 1918 which remained visible for 260 days. An example of an ordinary nova might be the object of +1431, 4 January, which disappeared after 15 days and reappeared 100 days later. This is reminiscent of a slow nova like DQ Her.

One example of a suggested identification that seems to be invalid is that of the radio source CTA1 with the object of +902. If the statement on the position 'beneath' Hua Kai (Cassiopeia) is correctly interpreted as 'south', the position $\alpha = 1^h30$, $\delta + 65°$ (1950), does not at all agree well with that of CTA 1, $\alpha = 0^h02.6$, $\delta + 72°20'$ (1950).

Changes of position seem to be clearly indicated. The object of +902 was most likely a comet.

Another example is the suggested identification of the source 3C386 with the object of +1230 that has recently been discussed by Mackay (1970). The object of +1230 was undoubtedly a comet (Ho, 1962). The optical evidence leaves little doubt that the object is extragalactic. The observed red-shift $z=0.0001$ is very small, but it must be corrected for the solar motion in the Galaxy to see how it fits into the red-shift-magnitude relation. The corrected value $z=0.0008$ (Schmidt, 1965) is still too small to be a safe distance indicator. If we take it literally, it gives a distance of 2.4 Mpc (with $H_0=100$ km sec^{-1} Mpc^{-1}). If the interstellar absorption is 3 magnitudes, the absolute magnitude is $M_p=-14.9$. The total power between 10^7 and 10^{11} Hz becomes $10^{38.8}$ erg sec^{-1}. The object seems to be a dwarf galaxy with very low emitted power. We do not know much about such objects; an object of this kind in the Virgo cluster would have a flux density of 0.63 fu at 400 MHz.

We are thus left with only 5 ancient objects that are identified as supernovae. Katgert and Oort (1967) have shown that this number is consistent with the estimated frequency of one supernova per 25 years in the Galaxy. Virtually the same frequency has recently been found by Tammann (1970). It is thus not to be expected that many additional supernovae are to be found in the ancient records. A review of Ho's catalogue shows, however, about 90 ancient objects for which there is no indication that they might have been comets. What were these objects? Some may actually have been tail-less comets. But, as I have pointed out, a large fraction, possibly the great majority, may have been and probably were bright ordinary novae. Another question calls for an answer: there are now about 90 nonthermal sources known that are believed to be supernova remnants; why are only 5 of them identified as remnants of historical novae? The answer is simple. Many of these sources are in highly obscured regions where interstellar absorption would blot out any supernova, and many of these sources are older than about 3000 years so that the parent supernova cannot be in the ancient records.

The determination of the age of a remnant is a complex problem. Needed are: (1) a model for the expansion, (2) parameters which depend on the location of the remnant in the Galaxy, distance and ambient interstellar density, (3) parameters which depend on the type of the supernova, initial energy of the explosion or initial velocity of expansion and ejected mass. None of the parameters can be determined with great accuracy. Relevant observational data are angular size, and flux density.

Shklovsky (1962) has suggested as a model the similarity solution for a strong explosion in a gas of constant heat capacity, given numerically by Taylor (1950) and in analytical form by Sedov (1959). Radiation losses in the gas behind the shock front are assumed to be negligible. This assumption is probably fulfilled for all observed remnants. The discussion of supernova remnants by Milne (1970) shows that the distribution of linear diameters has the form to be expected on the basis of Sedov's solution whose use thus has now observational support.

For the age of a source we then have

$$t = 8.3 \cdot 10^{26}\, n_{\mathrm{H}}^{1/2} E^{-1/2} r^{5/2} \tag{1}$$

or

$$t = 3.9 \cdot 10^{5}\, r v(t). \tag{2}$$

t is the age in years, r the radius in pc, n_{H} the number of interstellar H atoms per cm^{-3}, $n_{\mathrm{H}}/n_{\mathrm{He}} = 7$, and E the initial energy of the explosion in erg. $v(t)$ is the present velocity of expansion in km sec^{-1}.

Equation (2) looks deceptively simple, but it requires data which are not available except for one source, the Cygnus Loop (Minkowski, 1958). With the radius of 20 pc and the present velocity of expansion of 116 km sec^{-1} the age is 69000 years. Very similar to the Cygnus Loop is IC 443. For this object the available information is poorer; an assumed distance of 1.50 kpc leads to a radius of 10 pc. With the velocity of expansion of 65 km sec^{-1} (Lozinskaya, 1968), the age is 60000 years. Both objects are far too old to be remnants of supernovae to be found in any historical records.

The use of Equation (1) requires knowledge of E and n_{H}. The initial energy E must depend on the type of the supernova. Unless the distance is known, n_{H} cannot be found from the galactic distribution of H. There seem to be only three remnants with known ages and distances for which $E \cdot n_{\mathrm{H}}^{-1}$ can be determined with the aid of Equation (1). For Tycho's nova, a supernova of type I, En_{H}^{-1} is $1 \cdot 10^{51}$. For the Cygnus Loop En_{H}^{-1} is $5 \cdot 10^{50}$, for IC 443 it is $2 \cdot 10^{49}$. Both are believed to be remnants of supernovae of type II. For the radio remnants the type of supernova is not known. The distance can be found from the relation between surface brightness and linear diameter (Milne, 1970); such distances have uncertainties of about a factor 2. Individual ages from Equation (1) may be uncertain by a factor 10 and are not accurate enough to decide whether the age is less than 3000 years, the maximum age for objects in the historical records.

To obtain an estimate of the number of remnants in Milne's list that are younger than 3000 years, we assume $En_{\mathrm{H}}^{-1} = 5 \cdot 10^{50}$ as an average value that takes roughly into account that supernovae II are twice as frequent as supernovae I (Tammann, 1970). Equation (1) then permits us to compute the linear radius corresponding to an age of 3000 years. This gives a linear radius of 6 pc as the maximum radius for a source whose parent supernova might be found in the historical records. Since the historical records end about in +1600, sources must be excluded that are younger than 400 years and, according to Equation (1), smaller than 2.5 pc. Milne lists 25 sources with radii between 2.5 and 6 pc. Of these 10 are heavily obscured; their parent supernovae cannot have been seen. 12 are at declinations south of $-50°$ where the chance of the discovery of a supernova is small. This leaves three, plus a small number of objects with far southern declinations, to be compared with the five supernovae of +185, +1006, +1054, +1572, +1604 that are actually represented in Milne's list. It seems justified to conclude that very few, and perhaps no remnants are left that could be identified with old supernovae. Almost three quarters of the remnants are too old, the rest either too heavily obscured or too far south to be listed in the ancient records.

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Discussion

J. P. Ostriker: I would like to note that a recent analysis of pulsar observations gave a birth rate of about one per 35 years in the Galaxy, which within the errors agrees with the rate that you, Shklovsky, and Oort and Katgert derive for the occurrence of supernovae.

R. Minkowski: The frequency of pulsars that you suggest is indeed in complete agreement with the frequency of supernovae. One might wonder why there is not a pulsar in every supernova remnant. This may not be difficult to understand. First, beaming might make many pulsars unobservable. Second, the average distance of the known supernova remnants are larger, perhaps by a factor 5, than the distances of the known pulsars. Thus many pulsars in known supernova remnants might be too far away and too faint to be observable with the present means.