PART 3

SUPERNOVA REMNANTS

"Supernovae are called on to explain everything, and indeed they may, but I await further studies."

D. W. Goldsmith, in the discussion following his paper

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OBSERVATIONAL ASPECTS OF SUPERNOVA REMNANTS

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Abstract. A supernova event may lead to four observable features: a pulsar, an expanding nebulosity, a radio source and an X-ray source. The great majority of supernovae do not produce observable pulsars, and discussion is restricted largely to the other features. An increasing number of X-ray sources is now being detected and the structure and spectrum of the stronger sources investigated; these observations yield information about the physical state of the remnant. Recently, 11 new optical and radio remnants have been found in the Magellanic Clouds. These have led to a good determination of the $\Sigma - D$ relation, thus providing a more reliable distance scale for galactic SNR, but have also shown that a one-to-one correspondence between a radio source and a supernova event is questionable. When these remnants are combined with corrected earlier catalogues and a new southern catalogue containing a high proportion of distant old remnants the number of known SNR is about 150. The evolution of galactic SNR may be investigated empirically, and although the derived rate of occurrence is very uncertain a rate of about 2 supernovae per century is consistent with most determinations. The galactic SNR are distributed rather like the radio disc emission, but more closely confined to the galactic plane, and selected SNR show evidence of a spiral pattern.

I. Introduction

The observable remnant of a supernova comprises all or some of a number of features. The radio source is most obvious and is conventionally assumed to be common to all events but, in addition, the remnant may exhibit an optical nebulosity, an X-ray source and a pulsar. Other less certain features which may be associated comprise 'fossil' Strömgren spheres and expanding shells of neutral hydrogen, but there will be no time to discuss these. Pulsars will be considered only in their relation to the expanding remnants. From about 150 radio sources which have been classified as supernova remnants (SNR) with some degree of certainty, only two exhibit all four of the main features, the Crab nebula and Vela X. Of these, only the Crab nebula is also recorded as an actual supernova event. Nevertheless, there is little doubt that we are dealing with a common morphological class.

My task is made easier by the recent appearance of a comprehensive review by Woltjer (1972). A brief summary is therefore adequate for many of the observational features, and it is possible to discuss the most recent developments at some length. Woltjer's review also serves as a source of references for much of the earlier work.

II. Optical Features

Optical emission from SNR is observed only under favourable circumstances when the interstellar absorption is not too great. The remnants of 25 galactic SNR have been observed as filamentary emission nebulae (e.g., Woltjer, 1972; van den Bergh *et al.*, 1973) and, just recently, the numbers recognized in the Magellanic Clouds have increased dramatically from three to 14 (Mathewson and Clarke, 1972, 1973a, b, c). However, because of their great distance little detailed information is available on the

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latter. The filamentary structures of galactic supernovae display a wide variety of appearances, which are discussed and classified by van den Bergh *et al.* (1973).

Expansion of the filaments is observed for nine objects: Tycho's SN, the Crab nebula, IC 443, the Monoceros nebula, Pup A, Kepler's SN, the Cygnus Loop, HB21 and Cas A. No measurements of radial velocities or proper motions are available for the remaining nebulosities. Expansion velocities reported range from about 5500 km s^{-1} for Cas A (van den Bergh, 1971) to about 22 km s^{-1} for HB21 (Losinskaya, 1972). Cas A has a second, low velocity, filamentary system apparently formed from the stationary interstellar medium. The filamentary system associated with Kepler's SN also has radial velocities much lower than expected from the other characteristics of the supernova (Minkowski, 1959), and there are some similar difficulties with the Cygnus Loop (e.g., Tucker, 1971).

Woltjer (1972) has summarized the measurements of relative emission line intensities for nine SNR and compared them with the corresponding intensities in a typical H II region, the Orion nebula. A notable feature is the great strength of the [S II] doublet (λ6716–31), which is comparable or greater than Hα for the SNR but at least an order of magnitude weaker for the Orion nebula and the other H II regions. Other forbidden lines, particularly [N II] (λ6548 – 84), are also relatively much stronger in most SNR. However, Woltjer concludes that, after allowing for the great variations in T and N_e, most of the data are compatible with 'normal' compositions. Notable exceptions are the Crab nebula with an apparent over-abundance of He, and Cas A in which the H, N and O abundances appear anomalous. The relatively high strength of the [S II] lines is an excellent but not infallible indication of a remnant and has been used to identify SNR in the Magellanic Clouds, first by Westerlund and Mathewson (1966) and later by Mathewson and Clarke (1972, 1973a, b, c).

Observations of the emission spectrum have been used to estimate masses of the expanding gaseous envelopes, but these masses are lower limits because not all the gas is necessarily in a radiating condition. The overall picture is that the physics of the optical emission is reasonably well understood. Further observations are possible, particularly of the largely neglected southern objects, and future improved instrumentation should allow more detailed analysis of the SNR in the Magellanic Clouds.

III. X-Ray Emission

Soft X-ray emission from the hot gas behind the shock front of the expanding shell is expected and has been detected in all the well known SNR. Unfortunately, it is not yet possible to measure the spectrum with sufficient accuracy to decide whether the origin is thermal exept in one case, the Crab nebula. This, however, has a power law spectrum characteristic of synchrotron radiation and, moreover, it is linarly polarized (see Woltjer, 1972). The other remnants have spectra which can be equally well represented by power law or exponential spectra, corresponding to synchrotron and thermal emission respectively, and in most cases the agreement is not particularly good with either. Uncertainties arise because of interstellar absorption and the expected presence of emission lines in a thermal emitter, distorting the simple bremsstrahlung spectrum.

A detailed calculation of the effects of line emission and comparison with the measured soft X-ray spectrum of Pup A yields a very good fit at a temperature of 4×10^6 K (Burginyon *et al.*, 1973b). A similar temperature is obtained by a simple exponential fit, but the detailed agreement is not so good. The temperatures of this and four other remnants listed by Woltjer all lie within the range 2.5×10^6 K to 2.5×10^7 K whereas a much greater spread of temperatures would be expected from shock wave theory if the observed filament radial velocities are equated to the shock velocity. For slowly moving filaments, implying lower temperatures than those observed, there is reason to suppose that the shock is actually faster, as discussed by Woltjer (1972), but in Cas A the fitted temperature (1.4×10^7 K) would imply a shock velocity much slower than the velocities of the filaments. Possibly the synchrotron mechanism is dominant in young SNR, the relativistic electrons being supplied by a neutron star as for the Crab nebula.

Woltjer listed six SNR from which X-ray emission had been detected: the Crab nebula, Cas A, Tycho's SN, Pup A, Vela X and the Cygnus Loop. As a result of some recent surveys (Schwartz *et al.*, 1972a, b; Palmieri *et al.*, 1972; Giacconi *et al.*, 1972; Burginyon *et al.*, 1973a) a further seven identifications have been suggested with catalogued galactic SNR, although some of these are uncertain. In addition X-ray emission has been found from the region of the North Polar Spur (Bunner *et al.*, 1972), a possible SNR, as discussed later. An identification has also been suggested between one of the five X-ray sources in the LMC and an extended radio source (Byrne and Butler, 1973), but this does not have SNR characteristics. These new identifications are all comparatively weak X-ray sources and the spectra ill-defined.

A significant advance has been the detailed mapping of the X-ray emission from several SNR. The Cygnus Loop (Stevens and Garmire, 1973) has an associated X-ray source which closely corresponds in position with the radio and optical object. It displays marked limb brightening, suggesting confinement to a relatively thin shell, but the detailed correlation with other features is not good; the X-ray distribution suggests a more complete shell. Cas A (Fabian *et al.*, 1973) presents a similar picture within the limits of resolution. The most probable result is a shell source similar in size to the radio source, but a disc distribution cannot be excluded; a point source is most unlikely. Pup A (Zarnecki *et al.*, 1973) presents a different picture with the X-ray emission contained well within the radio source and strongly peaked in the NE quadrant; significant emission from a compact object cannot be excluded.

IV. Radio Remnants

The radio source is usually the basis for the recognition of a past supernova event. Radio sources come in two types, the extended, often shell-like object associated with the expanding remnant and characteristic of 'recent' supernova events, which we will subsequently refer to as the SNR, and the pulsar, believed to be the neutron star remnant, and usually associated with 'old' events.

I do not propose to discuss pulsars as such, although it seems very likely that the neutron star, which may not be an observable pulsar, could have an important relationship with the expanding remnant by providing a continuing source of energy in the early stages. Observational association of a pulsar and SNR is certain in only one case, the Crab nebula. However, the Vela X association is very probable, while a third recently suggested by Large and Vaughan (1972), the Crux SNR with PSR 1154−62, appears reasonable if one is prepared to accept a transverse velocity of about 600 km s^{-1} for the pulsar. Davies *et al.* (1972) have associated IC443 with PSR 0611+22, which is within $0\overset{\circ}{.}6$ of the centre of the SNR although well outside its outer boundary. The estimated distances of the objects are compatible but the ages appear incompatible; the association is discussed in Section VIII.

An attempt to associate all SNR with pulsars on a statistical basis (Tsarevsky, 1973) is clearly without foundation (Combe and Large, 1973). It seems necessary to accept the view that few supernova events produce a detectable pulsar although the proportion producing neutron stars may, of course, be much larger (even 100%).

One other possible association has been noted, the pulsar CP1919, which is located just within the boundary of a weak extended non-thermal source (Caswell and Goss, 1970). However, both the estimated distances and ages of the assumed SNR and pulsar are in gross discordance. It has been suggested by Blandford *et al.* (1973) that the extended source is a 'ghost remnant' of an old pulsar formed from the outward diffusion of the relativistic electrons. If so, other examples might be expected, but Schönhardt (1973) failed to find any such remnants in the fields of 19 'old' pulsars.

Let us now turn to the SNR proper. Characteristic morphological features are that the source forms a ring or arc-like structure, that it has a non-thermal spectrum (although this may be very flat and mimic a thermal spectrum), that the radio recombination lines are absent or at least very weak and that the radio emission exhibits linear polarization. These properties are well known and discussed by Woltjer (1972); some very brief comments are therefore adequate.

(a) STRUCTURE

All the catalogued SNR have been mapped with varying degrees of resolution. The most common characteristic is that of an irregular arc, but almost complete rings are not uncommon, and some quite amorphous structures have been classified as SNR. Generally, it has been found that every increase in resolution has led to an increase in the amount of detailed and irregular structure recorded, and it is clear that a model of a uniform expanding shell source is quite inappropriate. When shell sources can be recognized the thickness of the shell is typically of the order of 15% of the radius, but old SNR may have relatively thinner shells.

It is well known that the Crab nebula displays a central condensation rather than a ring structure, but it is difficult to understand how much older and larger remnants could have similar structures. It appears possible that such objects may be the ejected sources from nearby supernova events which have by chance met with very low densities in the interstellar medium or else the scattered remnants of super-supernovae.

There is evidence for both such processes in the Magellanic Clouds (Section VII).

Some evidence has been presented by Shaver (1969) that the emission in a sample of SNR tended to be greater in the directions perpendicular to the galactic plane. This would be expected if a significant proportion of the emission resulted from the compression of a predominantly longitudinal interstellar magnetic field. However, some recent analysis of other remnants has not provided such a clear picture (Willis, 1972).

Ring- and arc-like structures are also very common among H II regions and have resulted in many misidentifications. The application of other criteria are necessary to confirm that an object is an SNR.

(b) POLARIZATION

All well-resolved SNR exhibit linear polarization, which is usually distributed rather irregularly over the object (for recent work see Downes and Thompson, 1972; Milne, 1972a; Willis, 1972; Kundu and Velusamy, 1972; Kundu and Becker, 1972). The polarization is usually strongest at the highest frequencies, and there is evidence that the rotation of the plane of polarization is non-linear in λ^2, suggesting that internal Faraday depolarization may be effective (Velusamy and Kundu, 1973). The polarization is usually quite small, of the order of 5%, although values up to 25% have been quoted (e.g., Kundu and Becker, 1972).

The general low value of polarization, even at high frequencies, indicates a disordered magnetic field, but quite large-scale regularities in direction are found. For example, about half the SNR studied appear to possess largely radial fields, while a substantial minority give evidence for circumferential fields. However, observations at several frequencies are necessary to correct for the effects of Faraday rotation and obtain the true orientation, which may be in doubt in some of the published maps. There appears to have been no real correlation established between SNR and field direction or amount of polarization (e.g., Willis, 1972). Clearly more high frequency, high resolution observations are needed to clarify the situation.

(c) SPECTRA

All catalogued SNR display a nonthermal spectrum with a mean spectral index (defined by $S \propto \nu^{\alpha}$) of $\alpha \simeq -0.5$ with a dispersion of about 0.2. There is no indication that the spectral index is correlated with any other features of the SNR.

Generally, the evidence points to a simple power law spectrum at high frequencies, although there are some indications of a high frequency steepening for the Cygnus Loop (Kundu and Becker, 1972) and HB9 (Willis, 1972). Also many SNR spectra have a marked low-frequency turnover around 100 MHz or lower. Analysis appears to support the view that this is the result of free-free absorption (e.g., Dulk and Slee, 1972) but the origin of the absorption is not at present clear. According to Dulk and Slee it is likely to occur either in dense partially ionized H I clouds or in the intercloud medium.

V. Catalogues of SNR

During the last few years several comprehensive catalogues of SNR have been prepared by Milne (1970, 1971), Downes (1971) and Ilovaisky and Lequeux (1972a). These have become progressively more complete and reliable as accumulated observations lead to the recognition of more candidates and the more accurate classification of previously known objects. However, some uncertainties remain. For example, the most recent catalogue (Ilovaisky and Lequeux, 1972a) contains 116 galactic SNR but four are rejected in a footnote because radio recombination lines had subsequently been observed and, later, eight others have been similarly confirmed as H II regions (Caswell, 1972; Dickel and Milne, 1972; Dickel *et al.*, 1973). There is also the likelihood of contamination by extra-galactic objects because all the radio features common to SNR have been observed in well-identified radio galaxies. Several nonthermal sources close to the galactic plane are, in fact, believed to be extragalactic and have not been included in their catalogue by Ilovaisky and Lequeux, but it would be surprising if all had been recognized, particularly among the weaker sources of small angular size.

Two partial catalogues have recently increased the number of well classified SNR significantly. Clark, Caswell and Green (1973) list 27 mainly southern galactic SNR of high reliability; these are, on average, older and more distant objects than those in earlier catalogues. Mathewson and Clarke (1972, 1973a, b, c) have increased the number of well identified SNR in the Magellanic Clouds from three to 14; the latter are of great importance because of their accurately known distances and will be discussed separately.

Finally, at a much lower level of reliability we have the large galactic loops, such as the North Polar Spur, for which evidence is increasing of their similarity to SNR. The properties of five such loops ranging in size from about 5° to 120° are catalogued by Berkhuijsen (1973).

VI. Distances of Galactic SNR

The distances of relatively few galactic SNR have been determined, and none of these may be considered as precise measurements. The majority are kinematic distances derived from H I and molecular absorption lines; Ilovaisky and Lequeux (1972a) list 13 such distances and six in which lower limits can be obtained by this method. Other estimates are obtained by comparison of the radial velocities and proper motions of optical filaments, by association with stars or nebulosities where distances have been measured independently and by estimates of the brightness of associated historical supernovae.

Kinematic distances appear to be the most reliable but are available for only a small selection of SNR. The usual uncertainties arise because of the uncertain distance to the galactic centre, ambiguities in interpretation and the possibility of non-circular motions but, in addition, the irregular distribution of the absorbing matter is a serious complicating factor. Uncertainties by a factor of two or more are not unusual.

Estimates of the distances of Cas A, the Crab nebula and the Cygnus Loop have been made by combining the proper motions of filaments near the edge of the nebulosities and the radial velocities of more central filaments (cf. Woltjer, 1972). However, the possibility must be considered that because of selection effects low radial velocities are obtained leading to underestimates of the distances. There is also some evidence, as mentioned earlier, that the radial velocity of the filaments in the Cygnus Loop may be considerably less than that of the shock front.

The linking of SNR with other features such as OB associations, H II regions and dark nebulae may lead to accurate distances or to completely irrelevant results. Finally, estimates made from the brightness of supernovae deduced from historical records are very uncertain and do little better than separate the SNR into close and distant objects.

Although individual measurements are often unreliable, statistical improvement can be sought by making use of the empirical surface brightness-diameter relation (the $\Sigma - D$ relation). There is a correlation between these parameters implying similar evolutionary trends for all supernovae, as discussed in Section VIII. Various authors have derived empirical power law relations of the form $\Sigma = AD^{\beta}$ (e.g., Woltjer, 1972; Ilovaisky and Lequeux, 1972a), which may be used not only as a check on the calibrating SNR but to provide a scale for other SNR for which no other distance estimation is possible. However, the whole process is subject to the choice of calibrators and the weights assigned to them; marked differences exist between estimates of the constants A and β. Before discussing this relation we must look at the SNR detected in the Magellanic Clouds, which are unique in having accurate distances assignable.

VII. SNR in the Magellanic Clouds

Recently the results of two major investigations of the Magellanic Clouds have been published, one using the Parkes 64-m radiotelescope (McGee *et al.*, 1972a, b; McGee and Newton, 1972; Broten, 1972; Milne, 1972b), the other using a combination of radio measurements with the Molonglo Cross and optical measurements using the 1-m reflector at Siding Spring Observatory (Mathewson and Clarke, 1972, 1973a, b, c).

Three SNR in the LMC have been known for some time (Mathewson and Healey, 1964; Clarke, 1971). A list of eight new SNR candidates has been prepared by Milne (1972b) based on the Parkes work, but for the reasons discussed by Mathewson and Clarke (1973b) the measurements on these objects are misleading. SNR tend to occur in regions of recent star formation rich with H II regions, and the resolutions attained in the Parkes surveys appear to be inadequate to identify with certainty the different objects. Mathewson and Clarke confirm only two of Milne's SNR identifications and, moreover, find that the sizes given for these, based on the broadening of a 4′ beam, grossly exceed the size of the optical remnants. To make progress with SNR identifications in the Clouds based solely on radio data it appears that the beamwidth on one frequency at least should be $\lesssim 1'$, while to determine SNR structure a beam width $\lesssim 20''$ is desirable. Radio galaxy contamination is also a significant problem because

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the Cloud SNR are much fainter than their galactic counterparts, so that supporting optical data would always seem very desirable.

The technique of Mathewson and Clarke has proved very fruitful and the radio and optical emission of nine new remnants have been detected in the LMC and two in the SMC. The relative strengths of the [S II] doublet and Hα have been used as a criterion to identify an optical remnant. Two further identifications with emission nebulosities in the LMC were also suggested, but in these the characteristic [S II] remnant was not visible. Comparison of the Molonglo 408 MHz data (Le Marne, 1968) with a map prepared using the Fleurs Compound Grating Interferometer at a frequency of 1415 MHz and a resolution of 40″ (Christiansen, private communication) indicates that one of these is an H II region (N157B).

The well known SNR, N49, is interesting, as a second, weaker, nonthermal source having an associated patch of strong [S II] emission is found to be connected to N49 by filamentary structures, suggesting that it was ejected in the original supernova explosion (Mathewson and Clarke, 1973a). Another less obvious example is NIIL where there is a similar and much closer patch of [S II] nebulosity also with an associated weak radio source. The projected linear separation from N49 is 110 pc, consistent with the ejected material encountering an exceptionally low density in the interstellar medium. If similar features occur in the Galaxy they would not be recognized as physically related objects.

Two very extended nonthermal sources showing no associated [S II] emission are also discussed by Mathewson and Clarke (1973b). If these are located in the LMC they have linear sizes $\sim$200 pc, rather like the galactic loops, but their mean surface brightness is greater by an order of magnitude and no ring structure is apparent. Mathewson and Clarke consider that, together with the nonthermal source underlying the 30 Doradus nebula, they may represent fragmentary remains of very old super-supernovae. Westerlund and Mathewson (1966) suggested that there is evidence for such rare events in the distribution of Population I objects in the Clouds.

Mathewson and Clarke (1973b) have constructed a $\Sigma - D$ diagram from their reliably identified SNR in the LMC and have added a selection of the most reliable galactic SNR. This diagram is reproduced in Figure 1 with the addition of the SNR in the SMC (Mathewson and Clarke, 1972, 1973c), the other nonthermal sources discussed above and the two galactic loops for which direct distance determinations are available (Berkhuijsen, 1973). The solid line representing the best fit to the Cloud data is defined by $\Sigma_{408} = 10^{-15} D^{-3}$ W m^{-2} Hz^{-1} sr^{-1}. Among the Cloud objects significant departures from this relation occur only for the small nebulosity possibly ejected from NIIL and the two large extended sources. Among the well defined galactic objects the Crab nebula and the Cygnus Loop stand out as exceptions; it may be significant that the distances to both these objects have been obtained by their filament expansion rate. However, even among the sources with kinematic distances there is a slight discrepancy in the sense that the diameters of the galactic objects are about 15% less than those of the same surface brightness in the Clouds.

Many reasons can be advanced for the apparent difference between the galactic

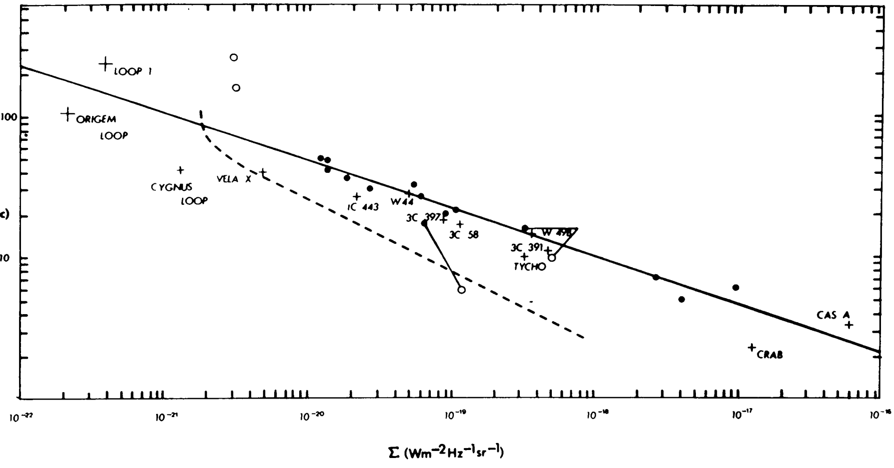

Fig. 1. The $\Sigma - D$ relation. Filled circles represent SNR in the Magellanic Clouds; open circles represent separate ejecta from the associated SNR plus the two low-brightness extended sources discussed in the text. Galactic SNR are indicated by crosses and named. The dashed line represents the approximate sensitivity limits of the radiotelescope.

and Cloud SNR. The important question, however, is whether the difference is real or the result of observational selection due to inadequate radio sensitivity in the Cloud searches. This seems unlikely. Although there is evidence of a strong selection in the detection of SNR in the Cloud this selection is based primarily on the strength of the [S II] doublet. A large number of nebulosities was examined but in no case was an optical remnant observed without a corresponding radio source. It therefore seems probable that the slope of the $\Sigma - D$ relation is quite well defined but that in applying it to determine the distance of galactic objects the constant multiplying factor should be reduced; this would obviously be necessary in comparing the distribution of SNR in the Galaxy with other features defined by kinematic distances.

In the remaining discussion I will adopt the relation suggested by Clark *et al.* (1973), $\Sigma_{408} = 7 \times 10^{-16} D^{-3}$ W m^{-2} Hz^{-1} sr^{-1}. Usually the relation is expressed at a frequency of 1000 MHz where, assuming a mean spectral index of -0.5, we have $\Sigma_{1000} = 4.5 \times 10^{-16} D^{-3}$ W m^{-2} Hz^{-1} sr^{-1}. This may be compared with the result of Ilovaisky and Lequeux (1972a), $\Sigma_{1000} = 4.6 \times 10^{-15} D^{-4.0}$ W m^{-2} Hz^{-1} sr^{-1}. The constant given by Ilovaisky and Lequeux has been corrected by the factor $4/\pi$ (e.g., Berkhuijsen, 1973). Other estimates based on the galactic SNR give similarly high exponents caused by the high weight given to Cas A and the Cygnus Loop in defining the slope of the $\log \Sigma - \log D$ relation (e.g., Woltjer, 1972). The relation may also be converted to a distance scale thus, $d = 49(S\langle\phi\rangle)^{-1/3}$ kpc where S is the flux density of the SNR in Jy at 1000 MHz and $\langle\phi\rangle$ its geometric mean diameter in minutes. This scale derived from the Cloud SNR gives closely similar distances to the various galactic scales for young SNR but increasingly greater distances for old SNR.

VIII. SNR Evolution

The evolution of SNR is largely the preserve of theory. Nevertheless, it is useful to discuss briefly the conclusions which can be reached by statistical analysis of the available observational data. As a starting point we assume that the data may be represented by the following set of equations:

$$\Sigma = AD^{\beta}, \tag{1}$$

$$\Sigma = Bt^{\gamma}, \tag{2}$$

$$D = Ct^{\delta}, \tag{3}$$

$$N = P\Sigma^{\xi}, \tag{4}$$

$$N = QD^{\zeta}. \tag{5}$$

In these, Σ and D have already been defined, t is the time in years elapsed since the outburst, N is the number of SNR in the Galaxy with surface brightness greater than Σ or diameter smaller than D, and the remaining symbols represent constants to be determined by observation. While it is known that these equations cannot represent the evolution of SNR over their whole lifetimes, we have seen already that Equation (1) appears to hold over a wide range of Σ and D. The equations are not independent, and if we assume a constant rate of supernova events there are three independent multiplying constants and two independent exponents.

Equations (1) and (4) are most directly accessible to observation. The former has already been discussed and the constants obtained at an observing frequency of 1000 MHz, $A = 4.5 \times 10^{-16}$, $\beta = -3$.

Equation (4) would seem to be easily obtained by a simple counting process, once we have a reliable and complete catalogue, but there are some difficulties. Firstly, the determination of Σ can only be performed satisfactorily when the remnant forms a ring or well-defined arc to which an angular diameter can be unambiguously assigned. Partially resolved or amorphous structures may represent the complete remnant, or only portions of a larger object. Secondly, the effects of selection are severe and tend to flatten the slope. Ilovaisky and Lequeux (1972a) have given careful consideration to the selection effect and derive a relation for a limited range of SNR diameters in the form $N \propto D^{3.15 \pm 0.70}$. Their $\Sigma - D$ relation ($\Sigma \propto D^{-4.0}$) may be removed from this result using the relation $\xi = \zeta/\beta$ to give the direct observational result, $\xi = -0.79 \pm 0.17$. The number of SNR with large diameters ($\gtrsim 30$ pc) falls drastically below this relation, which they ascribe to the difficulty of detecting such objects in the Galaxy. I have estimated the numerical constant P in Equation (4) from their Equation (5b) by assuming the total number of SNR in the Galaxy is 3 times the number in their sample area of radius 7.6 kpc centred on the Sun and, by using their $\Sigma - D$ relation and the number actually listed in their catalogue within this area (40). Thus $P \simeq 2.5 \times 10^{-14}$, with considerable uncertainty. The above estimates of ξ and P could be improved using the additional catalogue information now available, but a rough check indicates that the changes would be relatively small compared with the statistical and other uncertainties.

We have now enough information to derive the exponents of Equations (2) and (3), which describe the time evolution of SNR, thus: $\gamma = 1/\xi = -1.27 \pm 0.32$, and $\delta = 1/\beta\xi = 0.42$ with an uncertainty which is greater than ± 0.1 but which cannot be accurately specified because of the possibility of systematic effects in β. It is interesting that the latter exponent is close to the value of 0.4, the well-known Sedov adiabatic solution for an explosion in a medium of constant heat capacity, which should represent the expansion rate of SNR over a wide evolutionary range (cf. Woltjer, 1972).

Determination of the related constants B and C is not satisfactory as wide variations are expected in individual SNR and calibrating data are difficult to obtain. The expansion rate of young historically recorded SNR for which t is known is not likely to be described by our derived parameters. For example, it is known by direct observation of the filaments in the Crab nebula that $\delta \simeq 1$, as expected for an explosion unretarded by the interstellar medium. Similarly, the observed rate of decrease of the flux density of Cas A is not predicted by our equations, from which it is easily shown that $(1/S)\,(\mathrm{d}s/\mathrm{d}t) = (2+\beta)/t'$ where t' is the 'expansion age' obtained by extrapolating the observed proper motions of the expanding filaments back to the origin. Inserting the value of β obtained above and assuming an expansion age of 270 yr, the predicted rate of decrease is 0.37% per year, about three times less than the observed rate (cf. Woltjer, 1972; Findlay, 1972). Other historical supernovae cannot be checked so directly, but the combination of low age and locations far from the galactic plane, where the interstellar gas has a low density, makes them unreliable calibrators.

Older SNR must be used and their ages derived indirectly. There appear to be only two possibilities, Vela X and the Cygnus Loop, but both these are suspect because they lie below the adopted $\Sigma - D$ relation. If this displacement results from errors in the distances it will not affect our determination of B; if the estimated distances are correct the derived B will be too low. The age of the pulsar associated with Vela X has been estimated from the rate of increase of its period as 1.1×10^4 yr (Reichley *et al.*, 1970). When this age is inserted in Equation (2) we find $B \simeq 9 \times 10^{-16}$. The age of the Cygnus Loop may be obtained from the relation $t = \delta t'$, where t' is the expansion age, which is equal to 150000 yr (Minkowski, 1958). Taking $\delta = 0.42$ we find $t = 6.3 \times 10^4$ yr, leading to $B \simeq 9 \times 10^{-16}$ as before! The agreement is clearly nothing but a coincidence as both determinations are very uncertain. In particular there is some possibility that the Cygnus Loop is entering a late stage of evolution characterized by isothermal expansion for which $\delta = 0.25$ (e.g., Moffat, 1971); use of our equations would then lead to an overestimate of B. Taking $B \simeq 9 \times 10^{-16}$ as above we find $C = (A/B)^{1/3} = 0.79$, so that the expansion of a typical SNR is defined by $D \simeq 0.79\, t^{0.42}$. It is interesting to compare this with the Sedov solution, which gives $D = 0.65(E/n)^{1/5}\, t^{0.4}$ where E is the energy of the supernova explosion in units of 7.5×10^{50} erg (Shklovskii, 1962). Shklovskii's estimate that $E/n \sim 1$ for a typical supernova explosion is not very different from our result.

Finally, we may estimate the rate of occurrence of supernovae in the Galaxy using the relation $R = N/t = PB^{\xi}$. Inserting the values derived above we find $R \simeq 0.02$ yr^{-1}, or the mean time between supernova events $\tau \simeq 50$ yr. If, however, we assume that direct distance determinations of Vela X and the Cygnus Loop are correct and that the brightnesses are anomalous, we may çalculate the constant C from Equation (3). Thus for Vela X, $C = 0.58$ and for the Cygnus Loop, $C = 0.48$. Adopting the mean value, $C = 0.53$, we find $B = AC^{-3} \simeq 3 \times 10^{-15}$, leading to a mean time between supernova events $\tau \simeq 130$ yr.

It is interesting to compare these results with other determinations. Using Sedov's relation directly, with assumed values of E and n, Downes (1971) gives $\tau \simeq 45$ yr and Milne (1970) gives $\tau \simeq 75$ yr. Ilovaisky and Lequeux (1972b) base their calibration mainly on the historical remnants, with a theoretical correction for the density of the interstellar medium; they find $\tau \simeq 50$ yr. Recent direct determinations based on the observed rate of occurrence of supernovae in the Galaxy have been made by Katgert and Oort (1967) who find $\tau \simeq 26$ yr. Based on the rates in external galaxies Tammann (1970) finds $\tau \simeq 26$ yr for an Sbc and $\tau \simeq 65$ yr for an Sb. The range of estimated values is therefore about 5:1, with a most likely rate of about 2 per century. The estimates based on SNR should now be amenable to considerable improvement using new and improved catalogues and a combination of empirical and theoretical approaches.

The association of a pulsar with IC 443 by Davies *et al.* (1972) does not fit this general evolutionary picture. For the pulsar, $P/\dot{P} \simeq 125000$ yr, suggesting an age of about 60000 yr (e.g., Reichley *et al.*, 1970) but the SNR appears too small and bright for such an age. If its evolution had been typical, as defined above, the age should be about 6000 yr, but the corresponding transverse velocity for the pulsar would then be about 4000 km s^{-1}. If the pulsar is unassociated and formed in a supernova event 60000 yr ago its own remnant should be observable with properties similar to the Cygnus Loop. It may prove possible to reconcile these apparent contradictions without violating any observational data by assuming extreme values for all the parameters. An alternative hypothesis is that pulsars may be formed by direct contraction of a star without a typical supernova explosion (e.g., Cameron, 1970).

IX. Distribution of SNR

Several authors have discussed the distribution of SNR throughout the Galaxy (e.g., Milne, 1970; Ilovaisky and Lequeux, 1972a, b; Clark *et al.*, 1973). The most thorough statistical analysis is that of Ilovaisky and Lequeux, and although there is now much additional data which warrants further analysis it seems probable that their main conclusions will not be affected. Adoption of the present distance scale leads to an addition of between 20% and 25% to their mean distances. This hardly affects the overall shape of the derived radial distribution, but it does lead to a correction to the z distributions.

Ilovaisky and Lequeux found a scale height of about 90 pc for SNR within 6 kpc of the Sun. Using the present distance scale this should be increased to 110 pc, which, however, makes little difference to their discussion. The z distribution of SNR is very similar to that of the Cepheids, OB associations and OB stars and suggests a largely Population I origin. The detection of a few SNR, including remnants of some of the historical supernovae, at very high z distances is consistent with the generally accepted picture of a type I supernova associated with Population II and type II supernovae associated with Population I. It is clear that the great majority of galactic SNR must be of type II, and this would therefore be expected also in the Magellanic Clouds.

When the z distribution is derived as a function of distance from the galactic centre an increase of scale height is found as the distance increases. The same effect is observed in the z distribution of the nonthermal radio emission and H I (e.g., Mills, 1971) although the scale height of the SNR is less than either, in fact almost an order of magnitude less than that of the radio emission.

The surface density of SN remnants projected onto the galactic plane was also derived as a function of the distance from the galactic centre, assuming radial symmetry. When compared with the derived radial distributions of H I, H II and nonthermal radio emission it was found that only the latter displayed similarities. Both are restricted to little more than the solar distance and both have a fairly flat distribution out to this distance, although the radio emission does show more of a central concentration.

Clark *et al.* (1973) have prepared a map of the galactic distribution of SNR in their catalogue, together with those listed by Woltjer (1972) as good SNR identifications (Figure 2). They have used the distance scale presented here and limited the selection to SNR with $z < 250$ pc. Inspection of their map confirms that the SNR are distributed more or less uniformly out to 10 kpc from the galactic centre with a sharp decrease in numbers beyond. Within 10 kpc of the Sun the SNR are mainly confined to the regions of high H I density according to Kerr's (1970) map; in particular the Norma-Scutum arm is well delineated. Although the Sagittarius arm also shows up clearly there are some anomalies and the results do not really help to resolve the uncertainties in this region. However, the general appearance is that of a Population I distribution; in view of the uncertain distances of individual SNR little more can be expected.

X. A New SNR

Finally, the SNR associated with the supernova 1970g in M101 must be mentioned. This was a type II supernova discovered at the end of July 1970 in the southern part of M101 by Detre (1970). Weak radio emission (3.8 mJy) was reported at λ 11 cm by Gottesman *et al.* (1972) several months later, but by February 1972 the same group could detect nothing exceeding 3 mJy. Meanwhile, measurements at λ 21 cm using the Westerbork radiotelescope had detected a radio source having a flux density of 5.4 mJy in December 1970 and 11.3 mJy in December 1971 and at λ 6 cm a flux density of 4.0 mJy in January 1973 (Goss *et al.*, 1973).

Clearly, radio emission from the SNR has been observed, but the picture is complicated by the close proximity of an H II region (NGC 5455) in M101. Measurements of the Hβ flux for the nebula by Searle (1971) predict a radio flux density of only

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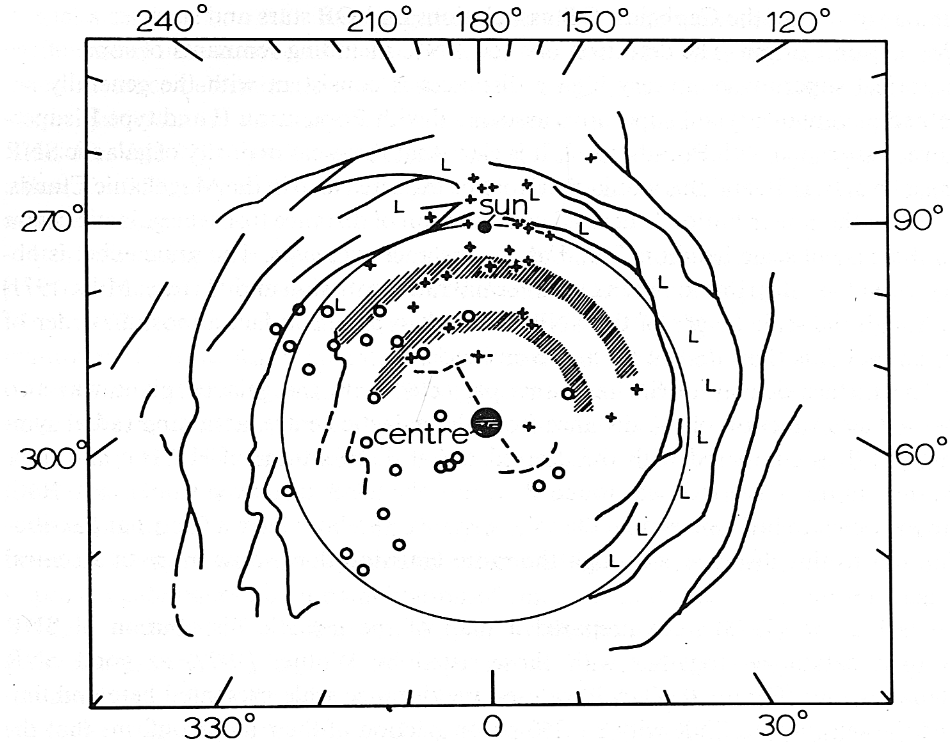

Fig. 2. The distribution of SNR in the galactic disk according to Clark *et al.* (1973) superimposed on the H I map of Kerr (1970). Open circles represent SNR from their catalogue; crosses represent well established SNR listed by Woltjer (1972). Selection has been restricted to those with $|z| < 250$ pc.

about 1.4 mJy, but there is evidence that Hβ measurements substantially underestimate the radio emission of H II regions in external galaxies (see also Mills and Aller, 1971). Most of the observed emission may be originating in the H II region, but even if one attributes to the SNR only the 6 mJy difference between the Westerbork 1970 and 1971 observations, the object would have several times the radio luminosity of Cas A. No convincing explanation for the observed emission has been advanced, and other recent extra-galactic supernovae studied at Westerbork have not been detected. One awaits its subsequent evolution with interest.

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DISCUSSION

Lequeux: It is interesting to see that the galactic distribution of SNR is not much affected by the choice of the $\Sigma - D$ relation used for determining distances. I doubt that distances to SNR are accurate enough to be able to establish a genuine association with galactic spiral arms.

Mills: The differences between the Ilovaisky and Lequeux $\Sigma - D$ relation and the one presented here do not affect the distances of the younger SNR very much, so I believe the radial distribution derived by Ilovaisky and Lequeux would not be greatly altered by the new scale. Since the true position of the galactic spiral arms is so uncertain perhaps the SNR will help determine them. There is clear evidence of spirality in the distribution.

J. R. Dickel: The shell thickness of old SNR is not necessarily thin. The plot of the thickness-to-radius ratio versus surface brightness shows tremendous scatter (A. G. Willis: 1973, *Astron. Astrophys.* **26**, 237). For example, the old remnant HB9 has a $\Delta R/R$ of at least 0.4.

Smith: It would be useful to measure the velocity of the pulsar close to IC 443, using the scintillation drift method. This would give an age as well as a test of the association, which at the moment rests on the fact that the pulsar is unusually young.

Mills: It is very important to pursue this possible association because we have so little information on the time evolution of SNR.

Oort: In a previous session, Goldsmith has stressed that we do not know where interstellar clouds come from. I think it is worth considering the possibility that they are generally generated by supernovae. If the radius of the disk is taken to be 12 kpc, its thickness 0.2 kpc, and if it is assumed a third of this volume is occupied by the spiral arms, the total volume is 3×10^{10} pc^3. If there is one supernova per 30 yr, we find that in a sphere of 100 pc radius there would on the average be one supernova explosion per 2×10^5 yr. This is of the same order as the probable life time of an SNR. It appears therefore possible that the 'clouds' in the interstellar medium as well as their velocities are created by supernovae.

Kerr: If the $\Sigma - D$ relationship is different for the Large Cloud and the Galaxy, could this be interpreted as a recalibration of the distance to the Large Cloud?

Mills: Either that or a recalibration of the distance to the galactic center. Either this distance would have to be increased by 10% to 15% or the distance to the Clouds reduced by this amount, provided the SNR in both places are the same. Alternatively it might be suggested that the Cloud SNR are brighter at the same diameter.

Lequeux: The apparent difference between galactic SNR and the SNR in the Magellanic Clouds can first be due to a selection effect: it is natural that one sees only the brightest SNR in the Clouds, whilst the sample of galactic SNR used to calibrate the galactic $\Sigma - D$ relation seems more random (these are just the SNR for which distances are known).

Mills: As discussed in my paper, the SNR in the Magellanic Clouds are strongly selected, but on the basis of the [S II] line brightness, *not* the radio emission. I would be surprised if only the stronger radio sources had been found, but of course this is not impossible.

Menon: You mentioned that the mean spectral index of supernova remnants is 0.5. Is it then possible to account for the nonthermal radio spectrum of the galactic background as being due to electrons from the remnants?

Mills: I do not know. Although there is clear evidence that the spectra of SNR do not evolve with time this applies only to the earlier phases. It is conceivable that changes may occur in the final stages of their evolution when merging into the galactic background.

Terzian: I like to report that very recently van den Bergh, Marscher, and myself published an Optical Atlas of Galactic Supernova Remnants (*Astrophys. J. Suppl.* **26**, (1973), 19), which should assist in making comparisons of the radio, X-ray and other maps with the optical ones.

Mathewson: All the supernova remnants in the Large Cloud I saw came in H II regions. Smith and Weedman determined the radial velocities of 70 H II regions in the Large Cloud and found that they agree to within a few kilometers per second with the H I. For two small supernova remnants which could be put right over the slit, the systemic velocities differed by about 70 km s^{-1} of the H I. Perhaps the supernova occurs in stars moving at high velocities, or it could be the sling-shot effect where the pulsar goes off one way and the remnant goes the other way.