SUPERNOVA REMNANTS RESEMBLING THE CRAB NEBULA

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While reviewing and systematizing the properties of the class of supernova remnants resembling the Crab Nebula it has been found that supernova remnants can be split into three morphological groups -- Class S (shells), Class P (plerions), and Class C (combinations) -- where the Class C objects appear to represent a new and especially interesting classification. In this overview, the identifying properties of all three classes are defined. Because the large Class S has been studied in detail many times previously, it is not discussed further here. For the smaller Classes P and C, the individual members and suspected members are presented and their properties reviewed. Finally, an origin and evolution for each class is suggested.

I. INTRODUCTION

In preparing a review of the members and radio properties of the galactic supernova remnants (SNR) which resemble the Crab Nebula (plerionic supernova remnants or plerions), it has become apparent that SNR exhibit a wider variety of forms than was previously recognized. Present information indicates that they can be divided into three morphological classes:

1) Class S (Shell supernova remnants)
2) Class P (Plerionic supernova remnants)
3) Class C (Combination supernova remnants).

Each of these will be discussed in turn.

II. CLASS S (SHELLS)

Of the 150-200 supernova remnants known in our Galaxy, it is apparent that the vast majority ($\geq$80%) are shells. Their identifying properties in each of the principal wavelength ranges are summarized in Table 1. Because they are the most common type of SNR, many members of the class have been studied in great detail and many reviews of their properties have been written. Thus, we will not concern ourselves

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further with them here.

Table 1. Identifying Properties of Class S

Radio
1) Non-thermal emission
2) Shell or partial shell form
3) Spectral index $\alpha \sim -0.45$ ($S \propto \nu^{+\alpha}$)
4) Weak integrated linear polarization
5) Rough adherence to a Σ-D relation
6) Circumferential or tangential magnetic field
7) Shock wave generated

Optical
1) Thermal line-emitting filaments
2) Shell or partial shell organization of filaments
3) Shock wave generated

X-Ray
1) Thermal emission
2) Both shell and filled-center forms seen
3) Shock wave generated

III. CLASS P (PLERIONS)

The Class P remnants form a much smaller group of SNR. Only about 5% or fewer of all known supernova remnants appear to fit the identifying properties.

Table 2. Identifying Properties of Class P

Radio
1) Non-thermal emission
2) Filled-center form extended emission
3) Spectral index flat ($\alpha > -0.3$; $S \propto \nu^{+\alpha}$)
4) Strong integrated linear polarization at high ν
5) Well organized magnetic field
6) General adherence to $S\,\theta^2$-d relation
7) Central energy source

Optical
1) Non-thermal emission (?)
2) Filled-center form extended emission
3) Thermal line-emitting filaments
4) Central energy source

X-Ray
1) Non-thermal emission

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2) Filled-center form extended emission
3) Compact source present
4) Central energy source

γ-Ray
1) Emitter (?)

Even though the existence of this class resembling the Crab Nebula was recognized over ten years ago (Weiler and Seielstad, 1971; Milne, 1971) and there have been many attempts to push any unusual object into the class (see, e.g., a recent review by Weiler and Panagia, 1980), the number of "true" plerions still appears to be very small. Only eight reasonable examples are known at present and only four of these are well established. The properties of the eight candidates are shown in Table 3 and discussed individually below.

G5.3-1.1 (Milne 56) - Table 3, Figure 1

After the detection of a number of x-ray sources near the galactic center by Bradt et al. (1971), one, GX5-1, was suggested by Milne and Dickel (1971) to be associated with a nearby supernova remnant G5.3-1.1. They showed that the remnant was indeed linearly polarized, and thus non-thermal, and had a filled-center form with the x-ray source included within the outer contours. The spectral index appeared to be straight from 0.6 to 5 GHz and unusually flat with an index of α=-0.2. They suggested a distance of 2.4 kpc. Clark et al. (1975) confirmed the flat radio spectrum down to 0.4 GHz and suggested that it might belong to the class of "amorphous" supernova remnants. Angerhofer et al. (1977) also confirmed the flat spectrum. Zealey et al. (1979) observed optical filaments in the vicinity of the radio source and re-emphasized the plerionic properties.

The properties of G5.3-1.1 are not well studied and the possible association with GX5-1 is not proven. Even the detection of a weak 1.4 GHz radio source at the x-ray position (Braes et al., 1972) does not necessarily establish a connection with the large radio supernova remnant. However, until more detailed studies are carried out in the radio and x-ray ranges, G5.3-1.1 must be considered as a possible plerion.

G21.5-0.9 - Table 3, Figure 2

The object has the filled center form, linear polarized radio emission, and straight and flat ($\alpha\sim0$) radio spectrum typical of the class. The plerionic nature of the source, which has been discussed earlier by Wilson and Weiler (1976b), Becker and Kundu (1976), and Weiler and Panagia (1980), has been confirmed by Becker and Szymkowiak (1981) with

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the detection of a filled-center, extended x-ray source coincident with the remnant. The properties listed in Table 3 are estimated for a distance of 15 kpc, the distance felt to be the most nearly correct (Weiler and Panagia, 1980; Becker and Szymkowiak, 1981). However, because HI absorption measurements (Caswell et al., 1975a) permit a smaller distance of $\sim$ 4.8 kpc, which is often used in the literature, calculated properties for the source at that distance are also included in the table.

G57.6-0.3 (4C21.53W) - Table 3, Figure 3

G57.6-0.3 is an unusual source which has been proposed by Erickson (1982) as a possible plerion. It has a filled center morphology and, at high frequencies (ν>150 MHz), a flat radio spectrum (α=-0.26). There is also a nearby (but not coincident) compact x-ray source (Erickson, 1982). The radio spectrum has a most unusual steepening at low frequencies (α=-2.4; ν<150 MHz) and there is no evidence for extended x-ray emission (Becker, private communication). No linear polarization is detected at either 6 or 20 cm (Becker, private communication). Direct application of the $S\theta^2$-d relation or a Σ-D relation yields the improbably large distance of $\sim$40 kpc. However, if a reasonable distance of $\sim$5 kpc is assumed for a galactic source, the object appears underluminous in the radio with respect to other plerions.

From the little known about it, the properties of G57.6-0.3 could also be consistent with those of an HII region or an extra-galactic source, but the unusual spectrum fits no single type of source well. Improved measurements are obviously needed at all wavelengths to determine the true nature of G57.6-0.3.

G74.9+1.2 (CTB87) - Table 3, Figure 4

An excellent example of the class, the radio properties of G74.9+1.2 have been thoroughly discussed by Weiler and Panagia (1980) and its plerionic properties by Weiler and Shaver (1978). The plerionic nature of the source has been confirmed by Wilson (1980) with the detection of a filled-center, extended x-ray source co-incident with the remnant.

G130.7+3.1 (3C58) - Table 3, Figure 5

The radio properties of G130.7+3.1 were first investigated by Weiler and Seielstad (1971) who suggested that it resembled the Crab Nebula. Wilson and Weiler (1976a) studied the source in more detail and Weiler and Panagia (1980) have discussed it in relation to other plerions. Van den Bergh (1978a, b) has found faint optical filaments at the position of the remnant and Weiler (1980) has discussed a correlation (like that known in the Crab Nebula) between the filaments and enhanced radio emission. Even though G130.7+3.1 has long been considered to be "the second Crab Nebula," strong confirmation by the detection of both compact and extended x-ray emission co-incident with the radio remnant has been gratifying (Becker et al., 1982).

The distance of $\geq$8 kpc given in Table 3 is estimated as a lower limit from HI absorption measurements (Hughes et al., 1971; Goss et al., 1973; Williams, 1973). A controversy has recently arisen due to new HI absorption measurements suggesting a smaller distance to the source (Green and Gull, 1983). However, with three independent older measurements in agreement and some question remaining concerning the sensitivity and spatial resolution of the new results, the best estimate of the distance remains $\geq$8 kpc.

G130.7+3.1 has been rather well connected to the supernova of AD1181 (Clark and Stephenson, 1977) and a Type II supernova origin (Panagia and Weiler, 1980). Thus, it is one of the small number of supernova remnants where the age and supernova type are reasonably well established.

G148+1 - Table 3

G148+1 is a small x-ray nebula $\sim$ 5' long trailing behind a pulsar with a period of $\sim$0.15. No radio emission is yet known and there seems to be little information available except the description presented by Helfand (1981, 1983). Although more measurements are needed to determine its nature, since G148+1 does show the x-ray properties of a plerion, it is included here. V. Radhakrishnan (private communication) has suggested that the source might represent the ultimate state of a very old plerion.

G184.6-5.8 (Crab Nebula) - Table 3, Figure 6

The Crab Nebula is certainly one of the most studied objects in the Universe. Its plerionic properties have long been known and until other members of the class were identified, it was either considered unique or lumped together with the Class S supernova remnants. The radio properties were studied in detail in a series of papers in the early 1970's (Wilson, 1972 and following) and more recently by Swinbank and Pooley (1979 and following). The Crab is, of course, optically identified and shows both thermal optical filaments and non-thermal diffuse optical radiation (see e.g. van den Bergh et al., 1973). It is, in fact, the only galactic source proven to emit extended, non-thermal continuum radiation in the optical range, although Vela X possibly does so (Weiler and Panagia, 1980). The Crab is known to contain a compact x-ray source (the pulsar) surrounded by extended x-ray emission. Gamma rays have been detected from the Crab pulsar.

The Nebula is well connected with the supernova of AD1054 and the distance is generally accepted to be $\sim$2 kpc. The supernova type of SN1054 has long been debated and was, for some time, considered to have been Type I. However, more recent results establish it rather firmly as having originated in a massive star (Hillebrandt, 1982; Davidson et al., 1982) and probably a Type II supernova (Chevalier, 1977).

An optical "halo" around the Crab has recently been reported (Murdin and

Clark, 1981) but Wilson and Weiler (1982) find that if the "halo" is evidence for a shell around the Crab, it is atypically weak in the radio range.

G328.4+0.2 (MSH15-57) - Table 3, Figure 7

G328.4+0.2 is often included in the lists of plerionic supernova remnants. It was studied by Goss and Shaver (1970) and Shaver and Goss (1970a) in their galactic survey work and included as a "possible" plerion by Weiler and Panagia (1980). It has a number of the radio properties of a plerion, including amorphous shape and flat spectrum (α =-0.24). Although it does not seem to have been studied for linear polarization, it has always been considered non-thermal in spite of its relatively flat spectrum. There appears to be no H109α emission (Shaver and Goss 1970b). No detection of x-ray emission from the source has yet been reported.

In spite of the relative lack of information and the fact that a thermal and/or extragalactic identification cannot be completely ruled out, G328.4+0.2 must be considered as a possible plerion due to its spectrum and radio morphology. Its known properties, however, are not entirely consistent. Caswell et al. (1975a) obtain a minimum distance of $\sim$20 kpc from HI absorption measurements. If this is correct, it implies from standard models that the object is half as old and twice as luminous as the Crab Nebula and expanding at the incredible average speed of 40,000 km s^{-1}. If the model of Weiler and Panagia (1980) is applied, the values (marked with superscript [a] in Table 3) are forced into a "reasonable" range but imply a much smaller distance. Thus, it appears that G328.4+0.2 is either mis-classified, much closer than 20 kpc, or a very extreme example of a plerion.

Thus, in spite of years of searching and many researchers trying to push new objects into the class, it appears that there are a maximum of 8 known Class P "true" plerions and two or three of these may be suspect. This implies that:

(a) plerions are short lived as Weiler and Panagia (1978) have suggested; or
(b) plerions are born only very infrequently as has been suggested by Srinivasan and Dwarakanath (1982); or
(c) both of the above.

However, the search for new objects has not been wasted. It has led to the development of what appears to be an entirely new class of very unusual objects -- the Class C plerion-shell combinations.

Table 3: CLASS P - Plerions

Name: Galactic	Name: Other	Position (1950): RA h m s	Position (1950): DEC ° '	Date SN	Age 10^3 Yrs	d kpc	/z/ pc	Size: arcmin	Size: pc	Ave. Expand Vel. km s^{-1}	Spectral Index α $S \propto \nu^{+\alpha}$	$S_{(1GHz)}$ Jy	L_{Radio} 10^7-10^{11}Hz erg s^{-1}	X-Ray Struct.	Comments	Fig.	References
G5.3-1.1	Milne 56	17 58 30	-24 50		12[a]	3[a]	60[a]	30x30	28x28[a]	1100[a]	-0.2	37	$1.9*10^{34}$[a]	CMPT?	possible	1	2,3,4,5,6
G21.5-0.9		18 30 47	-10 36		[2.3[a]]	15 / 4.8	230 / 75	1.3x1.3	5.7x5.7 / 1.8x1.8	[1200[a]]	0.0	6.4	[$1.4*10^{35}$ / $1.5*10^{34}$]	EXTD		2	1,7,20
G57.6-0.3	4C21.53W	19 37 30	+21 31		[1.7[a]]	40[a] / 5	200[a] / 26	1.7x0.7	19x8[a] / 2.5x1.0	[4000[a]]	-0.26	1.2	[$8.1*10^{34}$[a] / $1.3*10^{33}$]	CMPT?		3	8
G74.9+1.2	CTB87	20 14 10	+37 04		2.8[a]	≥12	250	9.4x5.9	33x21	4900[a]	-0.24	8.6	$5.4*10^{34}$	EXTD		4	1,9,10,21
G130.7+3.1	3C58	02 01 52	+64 35	1181	0.8	≥8	430	10x6	23x14	11000	-0.09	33	$1.5*10^{35}$	[CMPT / EXTD]		5	1,11,12,13
G148+1		03 55	+54		No radio emission known at present									[CMPT / EXTD]	{nature uncertain}		19
G184.6-5.8	Crab Neb.	05 31 31	+21 59	1054	0.9	2	200	7x5	4x3	1900	-0.26	1000	$1.6*10^{35}$	{CMPT / EXTD}	{pulsar / γ-rays}	6	1,14
G328.4+0.2	MSH15-57	15 51 44	-53 08		[2.6[a]]	≥20 / 9[a]	70 / 30[a]	6x5	35x30 / 16x14[a]	[2900[a]]	-0.24	15	{$2.6*10^{35}$ / $5.7*10^{34}$[a]}		possible	7	{1,15,16, 17,18}

[a]Estimated through the use of relations derived by Weiler and Panagia (1980)

References

1. Weiler and Panagia, 1980
2. Zealey et al., 1979
3. Milne and Dickel, 1971
4. Clark et al., 1975
5. Angerhofer et al., 1977
6. Bradt et al., 1971
7. Becker and Szymkowiak, 1981
8. Erickson, 1982
9. Wilson, 1980
10. Weiler and Shaver, 1978
11. Wilson and Weiler, 1976a
12. van den Bergh, 1978b
13. Becker et al., 1982
14. Wilson, 1972
15. Caswell et al., 1975a
16. Caswell et al., 1980
17. Goss and Shaver, 1970
18. Shaver and Goss, 1970a
19. Helfand, 1981, 1982
20. Wilson and Weiler, 1976b
21. Kazes and Caswell, 1977

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IV. CLASS C (COMBINATIONS)

The Class C-Combination sources are poorly studied at present. Their morphology, however, appears to be describable as a simple combination of a Class S-Shell with a Class P-Plerion (see Tables 1 and 2). Oddly enough, the Class already contains more objects than there are "true" plerions and, because it is so poorly studied, essentially all members offer extremely interesting examples for further study. The properties of the proposed members of the class are shown in Table 4 and discussed individually below.

G6.5-0.1 (W28) - Table 4, Figure 8

G6.5-0.1 is a large, shell-shaped, non-thermal supernova remnant located in a complicated region of the galactic plane. Observers have mapped its radio emission at a number of frequencies and distinguish a partial shell approximately 40' in diameter with linear polarization and a normal spectral index of $\alpha \sim -0.4$ (see e.g. Goudis, 1976; Dickel and Milne, 1976; Milne and Wilson, 1971; Kundu and Velusamy, 1972; Altenhoff et al., 1978). However, it contains a compact region, known as G6.6-0.1, which has a flat radio spectrum ($\alpha \sim -0.2$) but no linear polarization (Becker, private communication) and a nearby compact x-ray source (Andrews et al., 1982). There is also extended x-ray emission from the area (Long, 1979). Although the positional accuracy is not good ($\sim +1^{o}$), there is known to be a γ-ray source (2CG006-00) near W28 (Swanenburg et al., 1981).

The general source properties are described in Table 4, with those of the plerion (P) separated as well as possible from those of the shell (S). Although more detailed studies are needed, W28 appears to be a possible member of Class C.

G27.3+0.0 (Milne 62, Kes 73) - Table 4, Figure 9

G27.3+0.0 is a difficult source to discuss. It is in a complicated region of the Galaxy and the source structure itself is complex. Although it has an apparent shell shape, it may consist of unrelated parts both thermal and non-thermal. Angerhofer et al. (1977) and the references in Table 4 provide a good discussion of what is known about the source.

The source is included here because it is reputed to contain a compact x-ray source and thus may have at least one of the properties of the Class C objects. However, more detailed information is necessary to establish its nature.

G29.7-0.3 (Kes 75) - Table 4, Figure 10

G29.7-0.3 was classified as a supernova remnant in older catalogues due to its being extended and having a relatively steep spectrum ($\alpha \sim -0.7$).

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However, it was not until the source was well resolved by Becker and Kundu (1976) that it was shown to consist of several components with differing spectral indices. Recent work by van Gorkum, Shaver, and Salter (private communication) has now shown that G29.7-0.3 consists of a steep spectrum shell surrounding a flat spectrum filled-center component (Fig. 10). Extended x-ray emission is associated with the central component. The distance to G29.7-0.3 is estimated to be ∿7 kpc (Caswell et al., 1975a) from HI absorption measurements. From the observations presently available, G29.7-0.3 appears to be an excellent example of a plerion-shell combination.

G34.6-0.5 (W44) - Table 4, Figure 11

G34.6-0.5 is a large shell-type radio supernova remnant at a distance, from HI absorption measurements by Caswell et al. (1975a), of ∿3 kpc. Except for a slightly, but not unusually, flat radio spectrum ($\alpha \sim -0.3$) its radio properties generally resemble a normal Class S SNR.

However, x-ray observations have been reported (Pounds, 1980) from the Einstein IPC indicating that G34.6-0.5 does not show the usual thermal, shell-shaped x-ray emission of normal Class S remnants. It has an asymmetric, centrally peaked x-ray structure lying in the western half of the radio map. The x-rays from the center of the shell are soft, but the spectrum is harder from part of the region. This makes the remnant somewhat unusual.

While this is rather tenuous evidence from which to determine that G34.6-0.5 is anything but a normal, shell-type SNR, it is included here as a possible Class C remnant until improved radio and x-ray information becomes available.

G39.7-2.0 (W50) - Table 4, Figure 12

G39.7-2.0 is an object of currently great interest not so much for its supernova remnant properties, although it is unusual in being a filled shell, but because it contains, and is presumably powered by, the unusual "star" SS433. The radio remnant has an elongated shape, (Geldzahler et al., 1980; Downes et al., 1981) somewhat resembling the elliptical form of G130.7+3.1 (3C58) but with the sharp outer edge typical of a Class S-shell supernova remnant. The integrated spectral index of the source is exactly that of an average Class S source ($\alpha = -0.45$) but the spectral index distribution is still not well known. Associated with SS433 is both the compact and extended x-ray emission (Seward et al., 1980) typical of plerions.

Weiler and Panagia (1980) and Panagia and Weiler (1981) have suggested that G39.7-2.0 represents an extreme case of a shell-plerion combination where the plerion completely fills the shell. SS433 then serves as the energy source for the plerion in much the same way as the pulsar PSR0532 does in the Crab Nebula. This model predicts G39.7-2.0 will show a definite spectral index change from the "steep" spectrum shell ($\alpha \sim$

-0.45) to the "flat" spectrum plerionic filling (α >-0.3) and implies that the remnant is quite old (~30,000 years) and expanding very slowly (~300 km s^{-1}).

G68.9+2.8 (CTB80) - Table 4, Figure 13

Although the Class C sources are often unusual, G68.9+2.8 has to qualify as one of the most odd. Radio maps (Velusamy et al., 1976; Angerhofer et al., 1981) show it to consist of a very complicated, steep spectrum extended region with a smaller, flatter spectrum, possibly plerionic, "plateau" containing a compact, very flat spectum radio core. The source also contains both compact and extended x-ray emission from the "core" (Becker et al., 1982). Despite the lack of a clear shell shape in its large scale structure, measurements of optical line-emitting filaments in the area confirm the identification as a supernova remnant (Angerhofer et al., 1980). Angerhofer et al. (1980) estimate the distance to be ~3kpc from HI absorption measurements. The suggestion has been made that G68.9+2.8 is the remnant of the supernova of AD1404 (Strom et al., 1980).

Although the compact "core" of the source exhibits definite plerionic properies with resolved, filled-center radio structure at high resolution, a flat radio spectrum, and x-ray emission, the question remains whether the larger (~10'), somewhat steeper spectrum "plateau" is also part of the plerion. Until better information is available, we have included it as such. One must question further whether these are associated with the large scale "shell" or "shells." Again, for lack of other evidence, we have assumed so.

The possible association of the remnant with the "guest star" of AD1404 appears unlikely. Not only would such an age lead to an extremely high average expansion velocity for the extended remnant, Clark and Stephenson (1977) in their study of historical Chinese records accord the "guest star" a low probability of having been a supernova.

G93.7-0.3 (DA551, CTB104A) - Table 4, Figure 14

G93.7-0.3 possesses an unusual filled-shell radio morphology which reminds one of G39.7-2.0 (W50) (Mantovani, et al., 1982). Also, its integrated spectral index of α~-0.3 is somewhat flat for a normal Class S supernova remnant, although it is certainly within the deviation for normal shells. A weak, steep spectrum, compact radio source is known to exist within the shell at $\alpha(1950) = 21^h27^m13^s.1$, $\delta(1950) = +50^o23'37''$ but its connection, if any, with the remnant is unknown. Although G93.7-0.3 is included here as a possible Class C source, its membership in the class remains to be proven.

G263.9-3.3 (Vela XYZ) - Table 4, Figure 15

The Vela supernova remnant has recently been discussed in great detail by Weiler and Panagia (1980) and needs little further discussion here.

It is probably the best prototype of the Class C sources combining a large, non-thermal, steep spectrum radio shell (Vela YZ), with associated thermal x-ray emission, and a non-thermal, flat spectrum, plerionic radio component (Vela X), with non-thermal compact and extended x-ray emission. Its pulsar is also a source of γ-rays.

The Vela remnant has extensive, thermal, optical filamentary emission and a relatively well established distance of $\sim$0.5 kpc. From the pulsar spin down rate, the age of the remnant is known to be $\sim$12,000 years. After the Crab Nebula, Vela X provides the best chance for detecting non-thermal optical emission from a galactic supernova remnant (see e.g. Weiler and Panagia, 1980).

G320.4-1.2 (MSH15-52) - Table 4, Figure 16

G320.4-1.2 appears at first glance to be a normal Class-S remnant (Caswell et al., 1981) with clear optical thermal filaments (van den Bergh, 1978b) and an HI absorption distance of $\sim$4kpc (Caswell et al., 1975a). However, Seward and Harnden (1982) have found the Class C properties of extended x-ray emission from the source and an x-ray pulsar within its confines. The pulsar has the fifth shortest period ($\sim$0.15 s) and the greatest rate of increase of period of any pulsar known. Radio pulses have also been detected (McCulloch et al., 1982; Manchester et al., 1982).

Although there is 1.4 GHz radio emission exceeding 30 mJy per beam area in the area of the pulsar, there is no evidence for a prominent plerion. More detailed radio studies and a spectral index distribution measurement will be necessary to determine if the emission is unusual. However, an obvious discrepancy exists. A shell-type supernova remnant as large as G320.4-1.2 would normally be considered quite old ($>10^4$ years) while the dynamic age of the pulsar is quite young ($\sim$1600 years). Although a recent model by Srinivasan et al. (1982) can explain the discrepancy, proving physical association between the two objects and determining the details of their radio and x-ray properties is still necessary.

G326.3-1.8 (MSH15-56, Kes 25) - Table 4, Figure 17

G326.3-1.8 was the first object proposed as a Class C, shell-plerion combination. It is a perfect example of a steep spectrum radio shell with a flat spectrum plerionic remnant within its confines. Zealey et al. (1979) have found thermal optical filaments associated with the shell confirming its supernova remnant nature. Caswell et al. (1975a) obtained two possible distances (1.5 kpc and 4.6 kpc) for the remnant from HI absorption measurements and Weiler and Panagia (1980) argue for the correctness of the greater distance.

In spite of being an excellent example of a Class C remnant in its radio properties, G326.3-1.8 shows only diffuse emission associated with its shell in the x-ray range. It has no x-ray enhancement in the vicinity of the radio plerion (R.H. Becker, private communication).

G327.4+0.4 (Kes 27) - Table 4, Figure 18

G327.4+0.4 has a partial shell shape (Caswell et al., 1975b) and strong linear polarization confirming its non-thermal nature (Dickel and Milne, 1976). Its distance is estimated to be ~6 kpc (Lamb and Markert, 1981). G327.4+0.4 shows both compact and extended x-ray emission near its center (Lamb and Markert, 1981) which is near, but not co-incident with, a radio peak. A comparison of the 0.4 GHz and 5 GHz maps of Caswell et al. (1975b) suggests that this peak may have a flatter radio spectrum than the larger shell. G327.4+0.4 is also located within the error circle for the γ-ray source CG327-0 and may be associated with it (Lamb and Markert, 1981). The source thus appears very similar in morphology to G29.7-0.3 (Kes 75) and is a good candidate for being a Class C remnant.

G332.4-0.4 (RCW103) - Table 4, Figure 19

G332.4-0.4 appears to be a normal Class S remnant with a well defined radio shell shape, a spectral index of $\alpha \sim -0.5$ (Caswell et al., 1980), and a bright filamentary shell (van den Bergh et. al., 1973). Additionally, low resolution x-ray measurements show a circular region of presumably thermal emission co-incident with the radio shell (Lamb and Markert, 1981). There does remain some discrepancy over the probable distance to the object, with ~3 kpc being obtained from HI absorption measurements (Caswell et al., 1975a) and ~8 kpc from Σ-D estimates (Caswell et al., 1980). For Table 4 we have taken an average distance of ~6 kpc to estimate the intrinsic source properties.

G332.4-0.4 is unusual in that it contains a compact x-ray object centered on the shell remnant (Tuohy and Garmire, 1980) and is possibly associated with the γ-ray source CG333+0 (Lamb and Markert, 1981). There is no apparent excess radio emission at the x-ray source position and the radio shell does not appear unusually "filled." However, until more detailed radio and x-ray information becomes available, G332.4-0.4 must be considered a possible Class C remnant.

Even from the small number of examples presently available and the probability that some of the suggested members of Class C will prove to be misclassified, it appears that Class C (shell-plerion combinations) is larger than Class P ("true" plerions). Further, it is likely that the former class will grow as more Class S (shell) SNR are studied in detail. Class C is, in any case, unusual and provides an interesting area for study.

Although it is risky to split Class C, containing at most a dozen objects at present, into subclasses, there appears to be at least weak evidence for doing so. A possible subgrouping is illustrated in Figure 20.

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Table 4: CLASS C - Combinations

Name		Position (1950)		Date	Age	d	/z/		Size		Ave.	Spectral	$S_{(1GHz)}$	L_{Radio}	X-Ray	Comments	Fig.	References
Galactic	Other	RA h m s	DEC ° '	SN	10^3 Yrs	kpc	pc		arcmin	pc	Expand Vel. km s^{-1}	Index α $S \propto \nu^{+\alpha}$	Jy	10^7-10^{11}Hz erg s^{-1}	Struct.			
G6.5-0.1	W28	17 57 47	-23 20			2	3.5	P S	1 40	0.6 23		-0.2 -0.4	∿3 330	$6.0*10^{32}$ $3.5*10^{34}$	CMPT EXTD?	γ-rays?	8	2,3,4,5,6
G27.3+0.0	Milne 62 Kes 73	18 38 20	-05 06			Poorly defined remnant, structure uncertain									CMPT?	Class C?	9	7,8,9,10,11
G29.7-0.3	Kes 75	18 43 48	-03 02			7	37	P S	0.5 3	1 6		-0.15 -0.65	8.5	$6.6*10^{33}$	CMPT EXTD		10	12,13,14,15
G34.6-0.5	W44	18 53 45	+01 13			3	25		27	24		-0.3	230	$7.4*10^{34}$	EXTD	Class C?	11	3,5,12,29,33
G39.7-2.0	W50	19 09 21	+04 54			3	100		130x65	110x55		-0.45	86	$1.8*10^{34}$	CMPT EXTD		12	1,8,16,17, 18,19
G68.9+2.8	CTB80	19 51 36	+32 49	1404?	0.6?	∿ 3	150	P S	10x6 40	9x5 35	6000? 30000?	0.0 -0.6	2 100	$1.8*10^{33}$ $1.4*10^{34}$	CMPT EXTD		13	20,21,22,23
G93.7-0.3	DA551 CTB104A	21 28	+50 30			∿ 2	10		90	50		-0.3	40	∿ $6*10^{33}$		Class C?	14	8,24
G263.9-3.3	Vela XYZ	08 33 05	-45 37		12	0.5	30	P S	210x110 256	31x17 37	1000 1500	-0.1 -0.6	1100 650	$2.0*10^{34}$ $2.6*10^{33}$	CMPT EXTD	pulsar γ-rays	15	1
G320.4-1.2	Kes23 MSH15-52 RCW89	15 10 30	-59 05			4	85		30	35		-0.3	70	$3.6*10^{34}$	CMPT EXTD	pulsar	16	12,25,26,27
G326.3-1.8	Kes25 MSH15-56	15 48 24	-56 04			5	160	P S	15x8 36	20x12 30		-0.1 -0.4	40 100	$7.0*10^{34}$ $6.6*10^{34}$			17	1,12,28,29
G327.4+0.4	Kes27	15 45	-53 12			6	40		20	35		-0.6	33	$1.9*10^{34}$	CMPT EXTD	γ-rays?	18	30,31
G332.4-0.4	RCW103	16 13 48	-50 55			6	40		10	18		-0.5	27	$1.9*10^{34}$	CMPT	γ-rays?	19	12,36,38

P = plerionic component
S = shell component

References for Table 4

1. Weiler and Panagia, 1980
2. Andrews et al., 1982
3. Clark and Caswell, 1976
4. Milne and Wilson, 1971
5. Kundu and Velusamy, 1972
6. Altenhoff et al., 1978
7. Angerhofer et al., 1977
8. Velusamy and Kundu, 1974
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11. Caswell and Clark, 1975
12. Caswell et al., 1975a
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14. Becker and Kundu, 1976
15. Becker, 1982
16. Geldzahler et al., 1980
17. Downes et al., 1981
18. Seward et al., 1980
19. Panagia and Weiler, 1981
20. Angerhofer et al., 1980
21. Angerhofer et al., 1981
22. Velusamy et al., 1976
23. Becker et al., 1982
24. Mantovani et al., 1982
25. Caswell et al., 1981
26. van den Bergh, 1978b
27. Seward and Harnden, 1982
28. Zealey et al., 1979
29. Clark et al., 1975
30. Lamb and Markert, 1981
31. Caswell et al., 1975b
32. Tuohy and Garmire, 1980
33. Pounds, 1980

V. SUMMARY

The purpose of this review has mainly been to classify and briefly discuss the known supernova remnants without an attempt to develop models or explanations for their origin and evolution. However, from what is already known about several members of the classes, it is possible to assemble a somewhat speculative view of their origins. This is presented in Table 5. Detailed discussion, however, is reserved for future work.

Table 5. Origin

Class S (Shell)

1) White dwarf, low mass, old star
2) Type I optical supernova
3) No radio supernova
4) Complete stellar disruption
5) Strong shock wave formation
6) Shell-type remnant
7) Remnant long lived

Class P (Plerion)

1) Massive, young star
2) Type II optical supernova
3) Radio supernova
4) Stellar remnant remains (pulsar?, SS433-type?)
5) No strong shock or shock dissipated early
6) Remnant short lived

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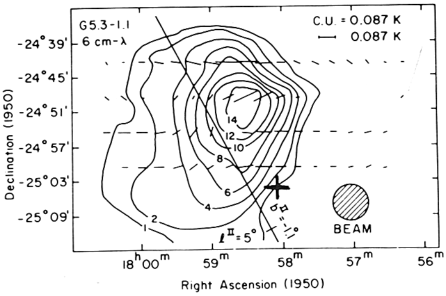
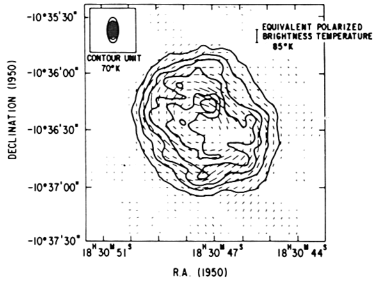
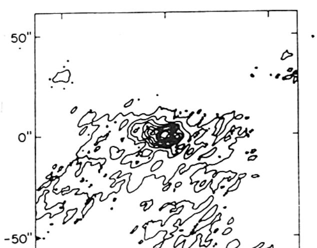
Class C (Combination)
1) Massive, young star
2) Type II optical supernova
3) Radio supernova (?)
4) Stellar remnant remains (pulsar?, SS433-type?)
5) Shock not fully dissipated
6) Plerionic remnant + shell remnant

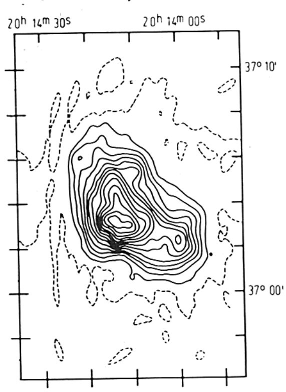
FIGURES



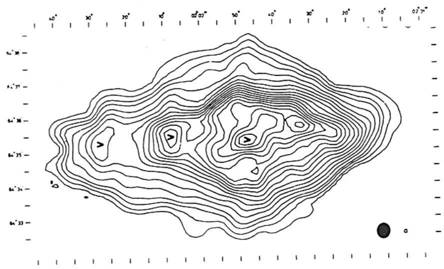


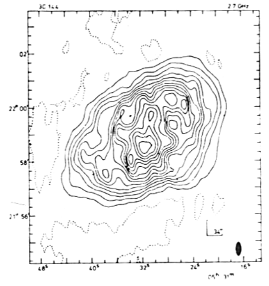
Figures 1 & 2: (Left) G5.3-1.1 (Milne 56) at 5 GHz (Angerhofer et al., 1977). The position of the x-ray source GX5-1 is indicated by a cross. (Right) G21.5-0.9 at 5 GHz (Becker and Szymkowiak, 1981).



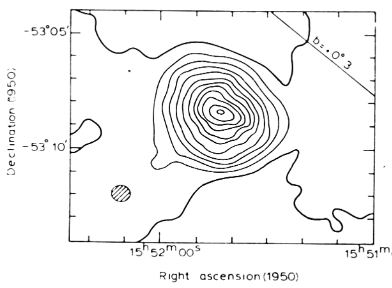


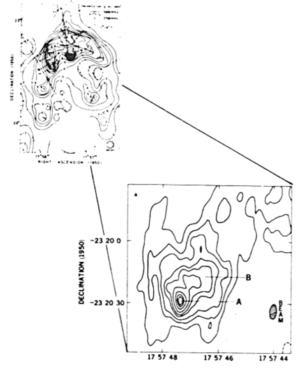
Figures 3 & 4: (Left) G57.6-0.3 (4C21.53W) at 1.5 GHz (Erickson, 1982). Field center coordinates are α (1950) = $19^h37^m29^s.61$, δ(1950) = $+21^o30'34''.0$. (Right) G74.9+1.2 (CTB87) at 1.4 GHz (Weiler and Shaver, 1978).



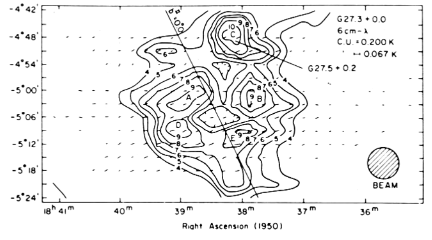


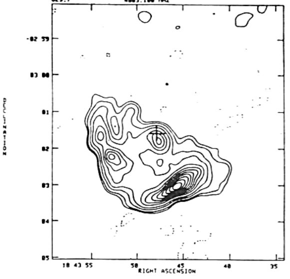
Figures 5 & 6: (Left) G130.7+3.1 (3C58) at 1.4 GHz (Wilson and Weiler, 1976a). (Right) G184.6-5.8 (Crab Nebula) at 2.7 GHz (Wilson, 1972).



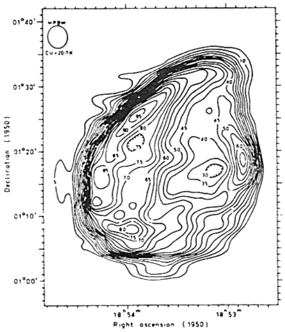


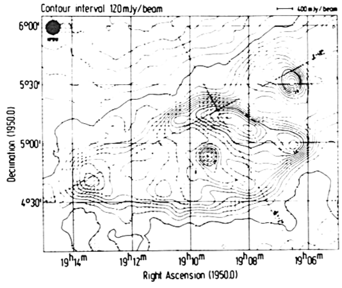
Figures 7 & 8: (Left) G328.4+0.2 (MSH15-57) at 1.4 GHz (Caswell et al., 1980). (Right, top) G6.5-0.1 (W28) at 5 GHz with a resolution of 4' (Milne and Wilson, 1971). (Right, bottom) Compact central region G6.6-0.1 at 1.4 GHz with a resolution of ∿5"x10" (Andrews et al., 1982).



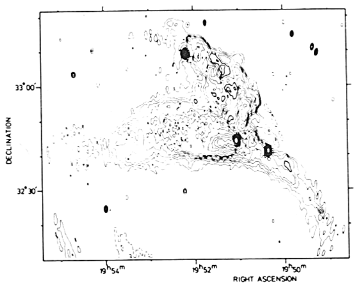


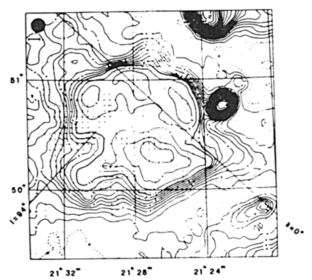
Figures 9 & 10: (Left) G27.3+0.0 (Kes73, Milne 62) at 5 GHz (Angerhofer et al., 1977). (Right) G29.7-0.3 (Kes 75) at 5 GHz (van Gorkum, Shaver, and Salter, private communication). The position of the x-ray emission is marked with a cross.



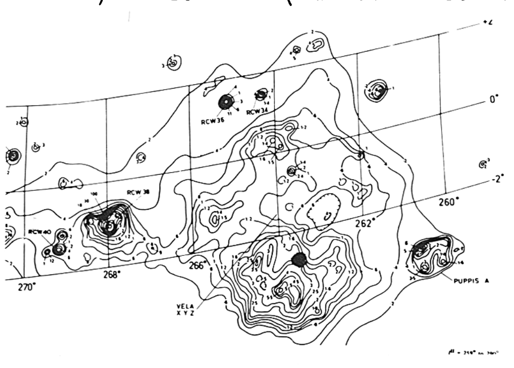


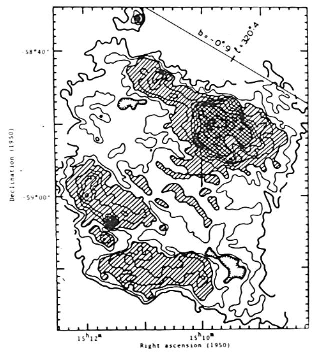
Figures 11 & 12: (Left) G34.6-0.5 (W44) at 0.4 GHz (Clark et al., 1975). (Right) G39.7-2.0 (W50) at 1.7 GHz (Downes et al., 1981). The compact source in the center is SS433.



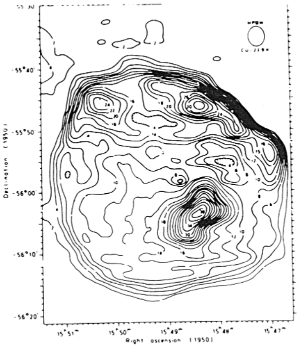


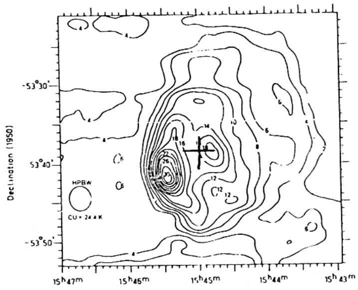
Figures 13 & 14: (Left) G68.9+2.8 (CTB80) at 0.6 GHz (Angerhofer et al., 1981). The compact feature near $\alpha = 19^h 51^m$, $\delta = +32^\circ 45'$ has spectral index $\alpha = 0$ and coincides with the x-ray source. (Right) G93.7-0.3 (DA551, CTB104A) at 1.7 GHz (Mantovani et al., 1982).



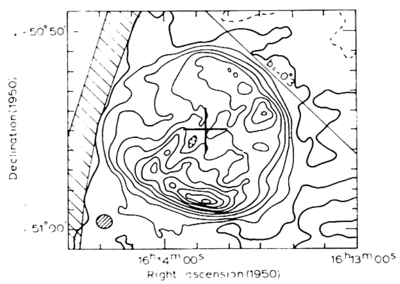


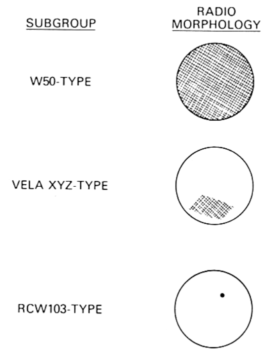
Figures 15 & 16: (Left) G263.9-3.3 (Vela XYZ) at 2.7 GHz (Day et al., 1972). The position of the Vela pulsar is marked with a spot. (Right) G320.4-1.2 (MSH15-52) at 1.4 GHz (Caswell et al., 1981). The position of the x-ray pulsar is marked with a cross.





Figures 17 & 18: (Left) G326.3-1.8 (MSH15-56, Kes 25) at 0.4 GHz (Clark et al., 1975). (Right) G327.4+0.4 (Kes 27) at 0.4 GHz (Caswell et al., 1975b). Position of the x-ray source is marked with a cross.





Figures 19 & 20: (Left) G332.4-0.4 (RCW103) at 1.4 GHz (Caswell et al., 1980). Position of the x-ray source is marked with a cross. (Right) Possible subgroupings of the Class C - Combination sources.

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DISCUSSION

WOLTJER: Before becoming too convinced that the Crab Nebula is the remnant of a Type II supernova, it may be good to remember that at its 200 pc distance from the galactic plane, massive stars are extremely rare. 3C58 may raise similar problems.

WEILER: Both historical and modern astrophysical arguments point toward a massive star - Type II supernova origin for the Crab. Although such stars are rare at that distance from the galactic plane, only one is needed to have given us the Crab Nebula. Even if all six relatively certain members of Class P are considered, the statistics are still too poor to estimate the scale height of their progenitors. If the pulsar in the Crab is typical of a young pulsar, then it is known that pulsars show a scale height distribution for their progenitors similar to that of Population I stars.

DICKEL: G21.5-0.9 showed tangential E vectors rather than a uniform field. Are there any other examples of that field orientation?

WEILER: No, not in any plerions where the polarization distribution is well known.

CHEVALIER: Although the Type II supernovae SN1979c and SN1980k were bright radio sources and SN1980k was a bright x-ray source, it is likely that the total radiated energy in the early phase was much smaller than the total kinetic energy of the explosion. Thus, this energy should still be available to drive a shock wave in the interstellar medium.

WEILER: I cannot disagree. One can speculate that very early dissipation of energy in the circumstellar material may weaken the shock enough that later interaction with the interstellar medium is insufficient to cause formation of a radio shell. However, there is no direct evidence for this. If this speculation is false, then the problem of what happened to the shells in the Class P ("true" plerionic) sources remains as before.

BISNOVATYI-KOGAN: When a plerion expands into the interstellar medium it may form a shell if the energy is sufficient. This was shown by T. Lozinskaya based on observations and on simple theoretical estimates. What can you say about this possibility and how many shell SNR could have been plerions?

WEILER: This is a difficult question. The Crab Nebula, for example, is certainly expanding supersonically into the interstellar medium, so that one might expect a shock wave to be present. However, it shows no evidence for limb brightening like historical SNR of similar age (Tycho, Kepler, etc.). Neither do any other of the Class P objects show limb brightening, although this is essentially by definition. <u>If</u> a plerion does eventually sweep up and accelerate relativistic particles to form a shell and <u>if</u> plerions are short lived with respect to shells as Weiler and Panagia have proposed, then the remaining shell would probably look quite normal leaving us little way of knowing which old shells were once plerions and which were always shells. One cannot rule out the possibility of an intermediate stage, however, where the plerion is fading but still visible. This might look something like Vela XYZ or the rest of our Class C-Combination remnants.

BEGELMAN: Can you comment on the morphology of radio polarization in the plerions, particularly those which appear elongated?

WEILER: There are no obvious systematics. In the Crab and 3C58 we find in one that the intrinsic polarization direction is parallel to the direction of elongation and in the other that it is perpendicular. G21.5-0.9, which is not elongated in its radio morphology, has polarization vectors which appear to run around in a circular pattern.

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