SUPERNOVAE -- BIRTHPLACE OF PULSARS?

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ABSTRACT

Recent developments in the theory of the light from supernovae indicate that while Type II supernovae probably involve the explosion of a massive star with an extended envelope, Type I supernovae may involve the total thermonuclear disruption of a white dwarf. The energy release in a Type II supernova is presumably related to the contraction of the core to a neutron star and pulsar formation is likely. The hypothesis that Type II supernovae leave pulsars while Type I supernovae do not leave compact remnants is shown to be consistent with the available information on X-ray sources containing neutron stars, young supernova remnants, and the distribution of pulsars in the galaxy. Some pulsars are probably formed in the explosion of a massive star that has lost its envelope. These events may not be accompanied by a bright supernova display.

1. INTRODUCTION

The association between pulsars and supernovae has been made on both observational and theoretical grounds. The best observational case is the Crab Nebula and its centrally located pulsar. There is almost no doubt that the Crab pulsar was formed at the time of the supernova of 1054. Another strong case is provided by the Vela supernova remnant and its pulsar. The pulsar is not centrally located, but this may be due to the expansion of the supernova remnant (SNR) into an inhomogeneous medium. The ages of the supernova remnant and the pulsar appear to be comparable. Other SNR-pulsar associations have been claimed, but the evidence is not convincing.

The idea that the formation of neutron stars is connected with supernovae goes back to Baade and Zwicky (1934), who realized that the energy released in supernovae is large and that the binding energy of a neutron star is a possible energy source. The details of how the energy is converted from binding energy to the mechanical energy of a

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supernova explosion have been the subject of intensive study in recent years.

Given the apparent association between supernovae and pulsars, the simplest assumption was that there is a one-to-one correspondence between supernovae and the formation of pulsars. The lack of an observed pulsar in some young remnants was attributed to beaming effects. Recent work indicates that such a close correspondence may not exist. Some supernovae may not leave a neutron star remnant and the formation of some pulsars may not be accompanied by a supernova display.

2. SUPERNOVA PROGENITORS

Evidence on the progenitors of supernovae is provided by observations of their location in spiral galaxies. Maza and van den Bergh (1976) found that while Type II supernovae (SNII) occur in spiral arms, Type I supernovae (SNI) occur throughout the disk of a spiral galaxy. Massive stars (mass greater than about 6 $M_\odot$) are confined to spiral arms, so the observations of position in spiral galaxies give a lower mass limit for SNII and an upper mass limit for most SNI. The hypothesis that SNII have massive star progenitors is consistent with both observations and theory, but the exact mass range in which they occur is uncertain.

The progenitors of SNI are less certain. Tammann (1974) noted that the rate of SNI per unit galactic luminosity is higher in spiral and irregular galaxies than in elliptical galaxies. In fact, the SNI rate is highest in irregular galaxies. Oemler and Tinsley (1979) took the analysis further and claimed that the SNI rate is proportional to the star formation rate in a galaxy. This would require that the lower limit on the mass of SNI progenitors be at least 1.5 to 2 $M_\odot$.

These properties may be difficult to understand if the progenitors of SNI are moderately massive single stars. First, there is observational evidence that some stars of at least 5 $M_\odot$ have evolved into white dwarfs and the most probable value for the upper mass limit for formation of white dwarfs is 7 $M_\odot$ (Romanishin and Angel, 1980). Thus, it is not clear whether the evolution of a single star with mass less than about 6 $M_\odot$ can lead to a supernova explosion. Second, a peculiar mass function would be required for the star formation in elliptical galaxies because SNI, but no SNII, are observed in elliptical galaxies. In spiral galaxies like our own, there are approximately equal numbers of SNI and SNII (Tammann 1978). Thus, the mass function in ellipticals would have to be cut off toward high masses. Finally, there is no direct evidence for star formation taking place in most elliptical galaxies. In particular, SNI are distributed throughout an elliptical galaxy, while star formation might be expected to be more centrally concentrated than the light from the galaxy. However, the rate of star formation required to explain the rate of SNI would not be directly observable with present techniques.

Although none of the above arguments is compelling, explosions in a mass transfer binary system seem to be more promising for SNI. A white dwarf in a low mass binary system can give rise to an explosion in an elliptical galaxy without any recent star formation (Whelan and Iben 1973). In spiral galaxies, white dwarfs with more massive (several $M_\odot$) companions can give rise to SNI and the rate of these supernovae would be proportional to the star formation rate. In both cases, the explosion of white dwarfs would have similar properties, as is observed.

3. SUPERNOVA MECHANISMS AND LIGHT CURVES

The study of supernovae near maximum light gives the most direct method of observing the supernova phenomenon and these observations have been the subject of detailed theoretical modeling (for a review, see Chevalier 1980a). The models show that if the energy deposition is instantaneous, a progenitor radius at least of order 3×10^{13} cm is required to obtain the peak luminosity of a supernova. If radioactivity is responsible for the peak light, at least 1 $M_\odot$ of Ni^{56} must be created in the explosion and the total ejected mass cannot be greater than 1-2 $M_\odot$ (Arnett 1979; Chevalier 1980b). A third possibility is that late energy is supplied by a pulsar.

For Type II supernovae, models with instantaneous energy deposition in an extended envelope appear to be the most appropriate. Models for the evolution of massive stars show that they end their lives with extended envelopes. The deposition of about 10^{51} ergs in such an envelope gives rise to an object with the detailed properties of a SNII (for references, see Chevalier 1980a).

The details of how 10^{51} ergs of mechanical energy is liberated as a result of the collapse of the central core are not yet understood. One possibility is that the ejection is driven by a reflected shock wave when the core bounces at nuclear density. Idealized calculations show that whether a bounce occurs is quite sensitive to the details of the equation of state (van Riper 1978; van Riper and Arnett 1978). In many cases, a collapse to a black hole is obtained. Another possibility is that convective overturn in the newly formed neutron star brings neutrinos to the surface where they may play a role in blowing off the outer layers (Colgate 1978; Bruenn, Buchler, and Livio 1979). In any case, it is plausible that the mechanism that gives rise to the energy of SNII leaves a neutron star remnant.

On the basis of the strength of the explosion, it is possible to estimate the amount of radioactive nuclei produced by explosive nucleosynthesis. Weaver and Woosley (1979) found that 0.1-0.4 $M_\odot$ of Ni^{56} may be synthesized during the explosion. Considering the large mass overlying the Ni^{56}, the radioactive energy input does not affect the properties near maximum light, but may contribute substantially to the light curve at late times.

Supernova models with pulsar energy input have been attempted, but do not seem very promising. Bodenheimer and Ostriker (1974) calculated models in which a pulsar provided the mechanical energy for the explosion as well as the energy for the peak luminosity. The models had too high a ratio of radiated energy to kinetic energy compared to SNII and all the envelope was accelerated into a thin shell which is inconsistent with the velocity evolution of SNII as deduced from spectral lines (Chevalier 1980a). Models in which the pulsar is only responsible for the radiated energy may be able to overcome some of these difficulties (Gaffet 1977a, 1977b), but detailed models for comparison with observations have not yet been performed.

If pulsars do contribute to the light of either SNI or SNII, they must be rotating quite rapidly at birth. At peak luminosity, a SNII radiates about 2×10^{43} ergs s^{-1}, while a SNI radiates about 4×10^{43} ergs s^{-1}. The Crab pulsar is one of the best observed pulsars with regard to period changes and it appears to have a braking index, n, of 2.5 (Groth 1975). Theories of pulsar spin-down predict n = 3. Assuming n has been constant at 2.5 or 3 over the age of the Crab pulsar, the initial rate of rotational energy loss of the pulsar was in the range 10^{39} to 10^{40} ergs s^{-1}, considerably lower than the maximum possible rate. This rate of energy production is consistent with the total energy now observed in the Crab Nebula. Ruderman (1972) notes that the slow rotation rate of white dwarfs may indicate that pulsars are born as slow rotators. There is no evidence that they are rapid rotators at birth, i.e., that their rotation rates are close to the maximal rotation rate. If all pulsars are born as slow rotators, then they cannot provide the luminosity for the peak luminosity of a supernova, although it is possible that a pulsar contributes to the late time luminosity. Chevalier (1977) suggested a model for the Crab Nebula in which the pulsar was not important for the supernova light curve, but was important for accelerating gas in the presently observed Crab Nebula filaments.

Thus, it is plausible that most SNII supernovae are accompanied by the formation of a pulsar, although the pulsar probably does not play a major role in the supernova light curve. It should be noted that the formation of a dense core is expected in massive stars up to a stellar mass of about 100 $M_{\odot}$. Beyond this mass, a pair formation instability leads to a thermonuclear explosion and complete disruption of the star (Barkat, Rakavy, and Sack 1967). There is no pulsar remnant in this case. Because this type of evolution occurs only in very massive stars, it is applicable to only a small fraction of the massive stars.

The nature of SNI is more controversial than the nature of SNII. However, there has been recent work which supports the hypothesis that radioactivity is responsible for the luminous energy of a SNI. The late time light curves of SNI show an exponential decay for hundreds of days. It now appears plausible that the decay can be explained by the radioactive decay of Co^{56} to Fe^{56} (Colgate and McKee 1969; Arnett

1979; Colgate, Petschek, and Kriese 1980; Axelrod 1980). The observed light curve decay is somewhat faster than the 77 day half-life of Co^{56}, but this may be due to either transparency of the expanding envelope to fast positrons or to an incomplete transformation of radioactive energy input into optical light. Axelrod (1980) finds that on the order of 1 $M_\odot$ must be ejected in order to prevent most of the luminosity from being emitted in the infrared. At late times most of the Co^{56} should have decayed to Fe^{56} and Fe is expected to be an important constituent of the expanding matter. Spectra at late times show the presence of emission lines which can be identified as Fe lines (Kirshner and Oke 1975; Meyerott 1980). Axelrod (1980) finds some evidence for Co lines as well as Fe lines and the Co/Fe ratio is approximately what would be expected on the radioactivity hypothesis.

Thus there is good evidence that the late time spectrum is due to radioactivity. The instantaneous energy input theory cannot apply because the cooling time is short compared to the expansion time. While a pulsar theory cannot be definitely ruled out, there is no detailed support for such a theory.

The amount of Ni^{56} required to give the late time luminosity is comparable to that required to produce the peak luminosity. Almost 1 $M_\odot$ of Ni^{56} must be synthesized to produce the peak luminosity (Arnett 1979; Chevalier 1980b). Chevalier (1980b) has computed detailed light curve models of SNI near maximum and obtained a good fit with observations for a 1.4 $M_\odot$ white dwarf undergoing C deflagration which produces 1 $M_\odot$ of Ni^{56}. The energy involved in the explosion is 1.3×10^{51} ergs and the white dwarf is entirely disrupted. Radioactive energy does not contribute substantially to the kinetic energy of the explosion, but provides the luminosity of the supernova. The hypothesis of a white dwarf explosion of SNI appears to be consistent with the evolutionary considerations discussed in the previous section. The theory suggests that SNI do not leave pulsar remnants.

4. EXPLOSION OF MASSIVE STARS WITHOUT ENVELOPES

Hydrodynamic models of normal SNII indicate that near maximum light we observe the expanding envelope of the progenitor star. This is supported by the fact that the expanding matter appears to have near normal abundances (Kirshner and Kwan 1975). However, under certain circumstances a massive star might end its life without its envelope. First, very massive stars have such strong winds that they lose their envelopes through mass loss. The mass loss is probably driven by radiation pressure. Such extreme mass loss may occur in stars with initial masses above about 30 $M_\odot$ (e.g., Chiosi et al., 1978; Dearborn et al., 1978). Second, massive stars in close binary systems cannot retain their extended envelopes. The envelope is lost to mass transfer and mass loss from the binary system.

The result of the mass loss is that the star explodes with a small radius (about 10^{12} cm). Chevalier (1976) computed light curve models for such an object. The peak luminosity was fainter than that of a normal supernova and the object spent only about one week near maximum light. The models assumed that radioactivity and pulsars were not important sources of energy.

Events similar to the models have not been directly observed. However, there is evidence that the stellar explosion that gave rise to the Cassiopeia A remnant was such an event. Observations of Cas A show both slow moving and fast moving material. The slow moving material can be identified with the envelope of the presupernova star and the fast material with the mantle of a massive star. The envelope was presumably lost before the star exploded. The Cas A event would have been easily observable in the 1600's if it had been a normal supernova. Even if Flamsteed did observe the supernova in 1680 (Ashworth 1980), it was about 6 magnitudes fainter than a normal supernova at maximum.

Thus it is likely that the Cas A event was the explosion of a massive star without its envelope. Chevalier (1976) argued that it was the explosion of a single star rather than a binary because there is not a companion star visible at the center of Cas A at present. If the mass were lost because of radiation pressure, a very massive star progenitor may be required. Fabian et al. (1980) note that the amount of X-ray emitting gas in Cas A is at least 15 $M_{\odot}$. However, one difficulty with the massive star hypothesis is that Cas A does not appear to be near an association of massive stars (van den Bergh 1971).

Because the stellar mass function drops toward high masses, the single star events may be relatively rare. On the other hand, a large fraction of massive stars may be born in binary systems and the binary type of event may be more frequent. In the late stages of evolution, the core of the star is expected to evolve relatively independently of whether the envelope is present. Thus, neutron star formation is expected to proceed at the centers of these stars. The result is potentially a massive binary X-ray source. The evolution of a binary system giving rise to an X-ray source with a neutron star has been described by van den Heuvel (1977). The explosion leading to the neutron star is that of a He star, i.e. a massive star without its envelope. Such an explosion is expected to be faint. The formation of an X-ray pulsar may not be accompanied by a normal supernova event.

5. NEUTRON STARS IN LOW MASS BINARY SYSTEMS

It appears that the population of non-extended galactic X-ray sources can be divided into two types (e.g., Salpeter 1973). Type 1 sources are associated with luminous massive stars. The events giving rise to these sources are described in the previous section. Type 2 sources are associated with the old stellar population -- the galactic bulge and the globular clusters. Joss and Rappaport (1979) have proposed a model for these sources involving accreting neutron stars or black holes, of mass $\gtrsim$ 1 $M_{\odot}$, in ultrashort-period binary systems with very low-mass ($\lesssim$ 0.5 $M_\odot$) stellar companions. In their model for the 7.7 sec X-ray pulsar, 4U 1626-67, Joss, Avni, and Rappaport (1978) proposed that the mass of the companion star is only 0.2 $M_\odot$. The advantages of the model are that it accounts for the apparent lack of conspicuous optical counterparts to the Type 2 sources and the apparent lack of X-ray eclipses. Joss and Rappaport (1979) suggest that the progenitors of these systems are cataclysmic variables and that the formation of the neutron star may take place in a SNI explosion. It should be noted that the Type 2 sources appear to be associated with an older stellar population than the SNI in spiral galaxies. Oemler and Tinsley (1979) find that the progenitors of SNI in spiral galaxies have masses of at least 1.5-2.0 $M_\odot$.

It is possible that the Type 2 sources have a different origin. Clark (1975) has argued that the sources in globular clusters are the result of capture into a binary system. A neutron star is created by the explosion of a massive star early in the life of the globular cluster. The neutron star eventually settles toward the center of the cluster because it is more massive than the typical cluster stars and it captures a low mass companion. It has been suggested that all of the Type 2 sources are formed by capture (e.g., Lewin 1980). This proposal would be consistent with the hypothesis that SNII and massive stars leave neutron star remnants while SNI do not leave compact remnants (see section 3).

However, the possibility that the evolution of low mass binary systems leads to neutron star formation cannot be ruled out. Canal and Schatzman (1976) find that electron capture in an accreting white dwarf can lead to collapse before an explosion occurs. The fate of an accreting white dwarf may depend upon the accretion rate. If the accretion rate is high, the central temperature may be relatively high and a thermonuclear explosion may occur. If the accretion rate is low, the central temperature may be low and electron capture may lead to collapse. If collapse does occur, it is probably not accompanied by a bright supernova event. Calculations of core bounce, which start with white dwarf structure, show that only the outer 0.1 $M_\odot$ is ejected (van Riper 1978), although this result is quite uncertain. However, the models for the Type 2 sources indicate a neutron star mass $\gtrsim$ 1 $M_\odot$, which imply a small amount of mass loss if the progenitor object is a white dwarf. Thus the supernova light cannot be produced by an instantaneous deposition of energy or by radioactivity. If the neutron star is initially rapidly rotating, pulsar energy input is a possibility, but detailed models reproducing the properties of a SNI have yet to be calculated. The other possibility is that if neutron stars are formed in this way, the event is not accompanied by a supernova display.

Besides the Type 2 X-ray sources, the other low mass systems with neutron stars are the binary radio pulsars. The first binary pulsar, PSR 1913 + 16 (Hulse and Taylor 1975; Taylor et al., 1976) is in an eccentric orbit with a short period, ~ 7.7 hr. The present situation is compatible with evolutionary scenarios in which the initial system was a massive binary (e.g. Smarr and Blandford 1976). The second binary pulsar, PSR 0820 + 02 (Manchester et al., 1980) is quite different in that is has a nearly circular orbit and a very long period, ~ 1710 days. It is not clear how this system would have survived a supernova explosion, especially because the estimated orbital velocity, about 5 km s^{-1}, is much less than the typical velocities (100-200 km s^{-1}) which pulsars appear to be given at birth (Taylor and Manchester 1977). The third binary pulsar (Damashek, Backus, and Taylor 1980) has a nearly circular orbit and a period of about 24 hours. The origin of the second two systems is obscure and it is not clear whether an origin in a low mass system is required.

6. SUPERNOVA REMNANTS

It was suggested in section 3 that there is a relation between the type of supernova event and whether a compact remnant is left. Except for the historical supernovae, it is generally unknown what type of supernova gave rise to any particular remnant.

The Crab Nebula is one remnant that definitely contains a pulsar. On the basis of the fragmentary observations of SN 1054, Chevalier (1977) suggested that the light curve is consistent with the supernova being of Type II. However, the properties of the nebula could only be reconciled with the properties of SNII if there is a fast moving shell surrounding the present Crab Nebula. There is no evidence for such a shell although searches have been made, particularly at radio and X-ray wavelengths.

The Crab Nebula is one of a class of supernova remnants with similar properties which have been called "plerions" by Weiler and Panagia (1978). The properties of these remnants based on radio observations are: 1) a filled-center or blob-like form; 2) a flat spectral index (~ 0 to -0.3); 3) a well organized internal magnetic field; and 4) high integrated linear polarization at high radio frequencies. In addition to the Crab Nebula, Weiler and Panagia (1980) find that there are five other probable remnants in this class. They are G 21.5-0.9, G 74.9+1.2 (CTB 87), G 130.7+3.1 (3C58), G 263.9-3.3 (Vela X), and G 326.3-1.8 (MSH 15-56). With the Einstein Observatory, it has been possible to show that some of these remnants are extended sources of nonthermal, X-ray emission (Weiler 1980). In the Crab and Vela, which are the only two remnants definitely known to contain a pulsar, the X-ray emission is concentrated toward the pulsar. These observations provide support for the conjecture that all the plerionic remnants are the result of pulsar activity. Some of the remnants are quite distant and it may be difficult to observe a fast pulsar in them because of the effects of dispersion; it is also possible that the pulsar radiation is not beamed toward us.

The remnant 3C58 is of particular interest because it has been identified with the supernova of 1181 on the basis of approximate spatial coincidence (Clark and Stephenson 1977). However, there is no compelling evidence for this identification. The remnant is quite elongated and the outer parts of it must have moved with an average velocity of about 14,000 km s^{-1} if it originated in an explosion of 1181. This is to be compared with an average velocity of 2,000 km s^{-1} for the Crab Nebula. Optical studies show only the presence of slow moving (several 100 km s^{-1}) material with near normal abundances (Kirshner and Fesen 1978). Panagia and Weiler (1980) find that the available information on the light curve of SN 1181 is consistent with that of a SNII so that if the remnant is properly identified with SN 1181, this may be further evidence for the association of pulsars with SNII.

Of the remaining historical supernovae, the events of 1572 (Tycho) and 1604 (Kepler) were probably of Type I and the available information on SN 1006 is consistent with it being of Type I. These supernovae have all been identified with remnants and none of them have plerionic properties. They are shell remnants and there is no evidence for central activity. Becker et al., (1980) have found that the remnant of SN 1006 does appear to have a nonthermal X-ray spectrum which they interpret as possible evidence for a central neutron star, but it is more likely that the fast electrons are generated near the supernova remnant shock wave (Reynolds and Chevalier 1980). The absence of an active pulsar does not rule out the presence of a quiet neutron star. However, the current theories of neutron star cooling indicate that the thermal emission from the central neutron stars should be observable with the Einstein Observatory. The remnants of SN 1006, SN 1572, and SN 1604 do not have observed central point sources, indicating that either the theory of neutron star cooling requires revision or SNI do not leave neutron star remnants (Helfand, Chanan, and Novick 1980).

The final type of young remnant is represented by Cas A, which probably exploded in the latter part of the seventeenth century. Cas A does not show any evidence for central activity and, again, there is no evidence for thermal emission from a neutron star (Murray et al., 1979). Shklovsky (1979) suggested that the compact remnant of the explosion is a black hole. This suggestion may be consistent with the argument of Wheeler and Shields (1976) that stars of initial mass $\sim 30\ M_{\odot}$ evolve to black hole formation based on their interpretation of the Cygnus X-1 binary system. Another possibility is that the progenitor was a very massive star which exploded because of the pair formation instability. This type of explosion is not expected to leave a remnant object and would be consistent with a large amount of mass loss from the progenitor star.

7. SPATIAL DISTRIBUTION AND RATES OF SUPERNOVAE AND PULSAR BIRTHS

While the distribution of supernovae in spiral galaxies is fairly well determined as discussed in section 2, the distribution of pulsars is more problematical because they can be observed only in our galaxy.

However, the discovery of pulsars has been proceeding at a rapid rate and now over 300 are known. Studies of the distribution of the pulsars (Taylor 1979; Harding 1980) show that there is a peak in the radial distribution near 5-6 kpc from the galactic center and there is some sign of peaks in the pulsar distribution at the tangential points of spiral arms. While the scale height of pulsars is quite large (about 350 pc), this can be attributed to the velocities which pulsars received at birth (Taylor 1979). The scale height for young pulsars appears to be less than 150 pc. These studies show that the distribution of pulsars is more consistent with that of SNII than that of SNI.

Tammann (1978) finds that the supernova rate in the Galaxy is about $(14\ \mathrm{yr})^{-1}$ and that the rate of SNI is approximately equal to the rate of SNII implying a SNII rate of $(28\ \mathrm{yr})^{-1}$. One effect that would tend to increase the rate is the obscuration of supernovae by dark clouds. Type II supernovae do occur in dusty regions of a galaxy, but the effect should not be large unless SNII preferentially explode inside dark clouds. At present, there is no definitive evidence for supernova remnants inside dark clouds.

Taylor and Manchester (1977) determined the rate of pulsar formation to be $(6\ \mathrm{yr})^{-1}$ on the assumption that the beaming correction is a factor of five. A slower rate would be indicated if pulsar beams are fan beams rather than pencil beams. In this case, more pulsars should be found associated with supernovae remnants, particularly in the plerionic remnants. The rate is determined on the basis of pulsar distances which are computed on the assumption that the mean electron density in the galaxy is $0.03\ \mathrm{cm}^{-3}$. If there is a region of low electron density near the sun, the distances would be underestimated and the rate would be overestimated (e.g., Mathewson 1979). There is a further weak argument that $(6\ \mathrm{yr})^{-1}$ is an overestimate of the pulsar formation rate. Considering the mass function for stellar births, this high rate suggests that stars less than 5-6 $M_\odot$ give rise to pulsars (see Fig. 9 of Miller and Scalo, 1979). This conflicts with the evidence that pulsars may be associated with spiral arms.

In section 4, it was argued that massive stars can explode, leaving a pulsar, but not giving a supernova display. There are two reasons for believing that most pulsars do not originate in this way. First, stellar evolutionary considerations indicate that most massive stars should end their lives with extended envelopes. Second, the faint explosions should deposit the same amount of energy into the interstellar medium as a normal supernova and they should result in the formation of a supernova remnant. There are large uncertainties in the remnant formation rate, but current estimates give a rate which is slower than the supernova rate rather than faster (e.g., Clark and Caswell 1976).

8. CONCLUSIONS

The arguments presented here indicate that SNII supernovae are associated with pulsar formation and that SNI are not. In addition some massive stars explode without a supernova display, but do leave a neutron star remnant. Briefly, the arguments are as follows: (1) The theory of the evolution of massive stars and of explosion mechanisms indicates that a neutron star is the plausible remnant of a massive star explosion. If the stellar envelope is present, this is a SNII; if the envelope is not present, the explosion may be a faint event. The theory of SNI light curves indicates that no compact remnant is left. (2) X-ray pulsars in massive binaries are consistent with an origin in massive stars. X-ray sources in low mass binaries may also be consistent with neutron star formation in massive stars if they are formed by capture. (3) There is weak evidence that plerionic supernova remnants, which appear to be powered by pulsars, are associated with SNII. On the other hand, the remnants of SNI show no evidence for central activity and strong upper limits have been placed on the temperature of a central neutron star. (4) The distribution of pulsars indicates that they are associated with spiral arms, as are SNII. Type I supernovae are not associated with spiral arms.

The main problem with this argument is that the pulsar rate is considerably faster than the supernova rate and the apparent rate of supernova remnant formation. However, the possible errors in these rates are probably larger than the differences between them.

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DISCUSSION

BLANDFORD: What fraction of plerions has associated pulsars? Could you estimate the beaming factor in this way?

CHEVALIER: Weiler and Panagia (1980) have listed six probable plerion remnants. Of these, two (the Crab and Vela) have associated pulsars. The fact that pulsars have not yet been detected in the other remnants may be due to factors other than beaming. For example, a pulsar may be difficult to detect against the remnant or the dispersion measure to the remnant may be large. In addition, the number of objects is too small to reliably estimate the beaming factor.

HELFAND: The X-ray data do not exhibit such a neat division into plerionic and non-plerionic remnants. In the case of the Crab Nebula only the synchrotron emission is seen, in Vela the expanding shell emission dominates, while another plerion shows an X-ray morphology similar to that of many other old remnants and the SNR with a radio shell plus plerionic center shows no activity in the center. Given our general ignorance concerning the origin of any kind of radio emission from SNRs it is perhaps premature to banish neutron stars from shell remnants and stick them all in plerions. This of course will also exacerbate the SNR-pulsar birthrate problem.

CHEVALIER: Actually, there is not expected to be a neat division into plerionic and non-plerionic remnants except for very young remnants. For a remnant with an active pulsar, the pulsar is expected to dominate the early evolution of the remnant (first few thousand years). The supernova itself does deposit a large amount of energy in the interstellar medium and, later, the interaction with the interstellar medium is expected to dominate. It becomes a shell remnant. It has been suggested that the remnant MSH 15-56 is intermediate between the plerion and shell phases.

KUNDT: If you discard some of the nearest kelifons (shell type SNRs) as the birth sites of neutron stars, the discrepancy between the numbers of pulsars and supernova remnants gets worse. You would then have to form neutron stars unnoticed. How do you hide the liberated binding energy?

CHEVALIER: The estimates of the rate of supernova remnant formation do give rates slower than the pulsar birth rate. However, there are many factors involved in the rate estimates which have large uncertainties and, in my opinion, it is not completely clear that the rates are different. If it is necessary to form neutron stars unnoticed, a possibility is the collapse of a white dwarf to a neutron star without mass ejection. The binding energy would primarily escape as neutrinos without direct observational consequences.

HELFAND: Has anyone recently re-examined the expected coincidence between pulsars and SNRs, now the numbers of both are much larger than in the original studies of ten years ago?

TAYLOR: SNRs are bright radio sources, easily detected anywhere in the Galaxy — even at distances of 15 - 20 kpc. In contrast, most of the 330 known pulsars lie within 1 or 2 kpc of the Sun. In other words, "average" pulsars are undetectable at the distances of "average" supernova remnants.

KUNDT: How do you explain the fact that all the flocculi in Cas A are blue-shifted and drifting north-northeast?

CHEVALIER: I have no particular theory for this fact, but a possibility might be that the progenitor of Cas A was a runaway star.

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