EPILOGUE

WHERE NEUTRON STARS COME FROM, HOW NEUTRON STARS EVOLVE, AND WHERE NEUTRON STARS GO

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At the end of this symposium, I shall briefly review our current knowledge on neutron stars.

Where have neutron stars been observed ?

430 Radio pulsars with periods between 1.5 ms and 4.3 s and magnetic fields $B_o \sim 10^{12 \pm 1}$ Gauss. Short periods are undoubtedly underrepresented in the sample because of more difficult discovery.

7 Radio pulsar binaries with B_o in the range $10^9 - 10^{12}$ G. Their luminosity is lower by a factor of 10 than for the singles, and essentially all are in the northern hemisphere. Hence, they are underrepresented in the observed samples by a factor of 15 - 20 in comparison with the singles. Additional selection effects may have to be considered. Binaries may therefore be somewhat less common than single pulsars but not by a large factor.

50 X-ray binaries, some with pulse periods ~100 ms - 1000 s. Quasi Periodic Oscillations (QPO) have been reported in several cases; if the beat models apply, rotation periods as low as 10 ms are involved. Cyclotron line observations in a couple of sources indicate fields up to 10^{12} G; if magnetospheric models apply to the QPO, more typical fields might be around 10^9 G.

15 Pulsar driven Nebulae, with in 3 cases a radio pulsar at the center. This might be taken as evidence of beaming factors around 0.2, but the systematics of these objects are still too poorly understood for firm conclusions.

~100 Gamma-ray bursters, the precise number depending on the repeat frequency, and the gamma-ray source Geminga; the association with neutron stars results mainly from the lack of plausible alternatives. Evidence has been presented for a periodicity of 8 s in the 1979 gamma-ray burst (from the source projected on N 49 in the Large Magellanic Cloud) and of 60 s in Geminga. The

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log N - log S relation for gamma-ray bursters may indicate distances of the order of 100 pc. If the 300 bursts observed in a decade were all from different sources, the phenomenon must be frequent in old neutron stars since their number within 100 pc from the sun is probably in the range 10^3 - 10^4.

Where do neutron stars come from ?

Undoubtedly many and perhaps all neutron stars originate in supernova (SN) events. Various types of SN are now recognized: I, I_{pec} (somewhat subluminous), II_{fast}, II_{slow}, II_{pec}, V (Zwicky's very slow type); SN I are the only ones to also occur in elliptical galaxies. A few dozen SN have been observed optically in adequate detail and only a few from the radio to the X-ray parts of the spectrum. Advances in stellar evolution calculations combined with observation indicate which stars are responsible for SN, but a detailed understanding of types still eludes us.

Stars with a main-sequence mass M_{ms} below 6 $M_\odot$ may become white dwarfs; this follows from the presence of white dwarfs in clusters with a main-sequence turn off mass of this magnitude. Of course, it does not follow that all stars with $M_{ms} < 6$ $M_\odot$ become white dwarfs.

The situation for stars with M_{ms} between 6 and 8 $M_\odot$ is unclear, but calculations indicate that in the range 8 - 10 $M_\odot$ neutron stars are likely to be produced. Arguments have been presented that the Crab Nebula resulted from such a star; problems remain with the CNO abundances, unless these are concentrated in dust grains for which the IRAS data have given some evidence.

Stars with M_{ms} between 10 and 25 $M_\odot$ may account for the typical SN II, although the precise "bounce" mechanism is still in some doubt; neutrinos probably play an important role. Nucleosynthesis calculations account in a quantitatively satisfactory way for some fifty solar system isotope abundances. Neutron stars probably are commonly formed.

For $M_{ms} > 25$ $M_\odot$ the situation is unclear. A black hole collapse is a definite possibility, since with increasing mass it becomes progressively more difficult to have a sufficiently strong bounce for the resulting shock to reach the surface. The number of such stars is too small in any case to affect neutron star statistics significantly.

Evolved stars in binaries are also likely important in neutron star formation. In particular, accretion induced collapse and explosion of white dwarfs may perhaps account for SN I; whether a neutron star remains after such events is uncertain.

While some work has been done on the effect of rotation on the collapse, much remains to be done in this area.

How can properties of neutron stars be understood ?

We shall now see how well the observed properties of neutron stars can be accounted for on the basis of the simple evolutionary picture.

Rotation periods. Much angular momentum has to be lost during stellar evolution; convection and/or magnetic fields are effective in transporting it outwards. There is no particular problem therefore in accounting for the observed periods, even if the initial periods were rather long (0.5 s) as has been suggested. If magnetic fields play the dominant role, weak field pulsars would be expected to rotate fastest. While there seem to be observational indications for this, the effects of field decay and recycling of old pulsars complicate the interpretation. The whole question of angular momentum in the later evolutionary phases needs further study.

Magnetic fields. Fields of the order of 10^{12} G are not at all unexpected. Internal fields built up by convection in the core on the main sequence or later would, with subsequent flux conservation, have such values.

Masses. Predicted masses from evolutionary calculations appear not unreasonable although perhaps on the low side by 10 - 20 per cent. The observed masses for the two neutron stars in the binary pulsar (1.45 and 1.38 $M_{\odot}$) are by far the most accurately determined masses outside the solar system.

Space velocities. Binary effects certainly account for some of the observed velocities (which range up to 400 km/sec), but it is doubtful that they account for all. Modest asymmetry in the supernova explosion may well be of much importance. Such asymmetry might result from an asymmetrical magnetic field distribution. Strong asymmetries between the two magnetic poles are frequently observed in magnetic A stars, and the resulting pressure distribution could start the explosion on one side. An observed tendency of low velocities to coincide with low magnetic fields as well as the lower field values in binaries are consistent with such a picture, but again field decay complicates the interpretation. Finally, the observed very asymmetrical location of the X-ray Crab Nebula and of the related optical activity indicates that asymmetrical particle acceleration also may play a role.

Formation rates. Data on supernovae, supernova remnants and pulsars in our galaxy are all consistent with a formation rate of one per 50 years. However, the uncertainties remain very large. The supernova rate is uncertain by a factor of about three because of the small sample and because of the possible importance of subluminous SN (like 3C 58 and Cas A). With a distance scale D and lifetime t, the supernova remnant formation rate in a disk galaxy is proportional to $D^{-2}\ t^{-1}$ or D^{-3} if the expansion velocities are known from X-ray temperatures. An uncertainty of a factor of three can therefore not be excluded. Finally, the pulsar formation rate varies as $D^{-2}\ t^{-1}\ \psi^{-1}$ with ψ the opening angle of the beam. With D, determined from dispersion measures, requiring a model of the electron density distribution in the galaxy and t depending on a model for the field evolution, and with ψ and its evolutionary variation being still very much in doubt, an uncertainty in the pulsar formation rate of a factor of five seems plausible. In fact, just a few years ago, formation rates as high as one per 7 years in our galaxy were sometimes quoted. Obviously with such large uncertainties, the statistics do not allow us to answer questions like whether all supernovae result in pulsars or whether all pulsars come from supernovae.

What is the further evolution of neutron stars ?

An isolated neutron star with a magnetic field will generally spin down by angular momentum loss from its surface. However, "glitches" may occur, related to the coupling mechanism between the crust and the interior. While such glitches have been frequently observed in young pulsars, a remarkably large event in an older pulsar was reported here.

Magnetic fields generated by currents in the crust of a neutron star are likely to decay on time scales of a few million years. Some evidence was presented that the decay may stop at about 10^9 G, possibly because of currents in the superconducting interior. The dipolar or multipolar character of the late field is still a subject of debate and affects estimates of its strength.

Cooling calculations for neutron stars have been developed in much detail. While for most neutron stars the predicted thermal X-ray fluxes are well below observed upper limits, in a few cases there appears to be a discrepancy; this may indicate the action of more exotic cooling mechanisms (pion condensation, etc.).

The long term result of the steady production of neutron stars will be the creation of a galactic halo of high velocity objects. Their total mass is unlikely to be of much dynamical significance (10^8 - 10^9 $M_\odot$). But perhaps the gamma-ray events show that there is still much activity possible in old neutron stars and that their nature is not yet fully understood. In fact, it even has been suggested that not all neutron stars are made of neutrons.