VIII. NEUTRON STARS IN BINARY SYSTEMS

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MASSES OF NEUTRON STARS IN X-RAY BINARY SYSTEMS

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The masses of 6 neutron stars have now been established through studies of binary X-ray and radio pulsars. All of the masses are found to be consistent with, but not necessarily constrained to, the range 1.2-1.6 $M_{\odot}$. In this talk we discuss the methods and assumptions used in determining the masses of neutron stars in binary X-ray pulsar systems. For other recent reviews of this subject, the reader is referred to Bahcall (1978), Rappaport and Joss (1981), and references therein. Neutron-star parameters may also be obtained from studies of X-ray bursts that result from thermonuclear flashes near the surface of an accreting neutron star (see Joss 1980 and references therein), which we will not discuss here.

There are currently about 18 known binary X-ray pulsars, with pulse periods ranging from 0.7 s to 835 s. Compelling evidence that these objects are indeed magnetic neutron stars comes from studies of their pulse period histories. The long-term secular decrease in pulse period, first observed in Her X-1 and Cen X-3 (Giacconi 1974; Gursky and Schreier 1975; Schreier and Fabbiano 1976), is found in at least 8 other binary X-ray pulsars (see, e.g., Rappaport and Joss 1981). Both the magnitude and sign of this "spin-up" behavior are in excellent agreement with theoretical predictions of the torques exerted on a highly magnetized, accreting neutron star (see, e.g., Pringle and Rees 1972; Lamb, Pethick and Pines 1973; Rappaport and Joss 1977; Mason 1977; Lamb 1981). Further direct evidence for the presence of magnetic fields of the order of several times 10^{12} G is provided by the identification of possible cyclotron line features in the spectra of two of the X-ray pulsars (Trümper et al. 1978; Wheaton et al. 1979).

In general, the determination of the masses of neutron stars in binary systems requires a knowledge of the orbital elements of the system. The neutron-star orbit can be measured by tracking the pulse arrival times over a suitably long time interval (see, e.g., Schreier et al. 1972). The X-ray mass function is then determined from the orbital parameters:

$$f(M) = \frac{4\pi^2}{G} \frac{(a_x \sin i)^3}{P_{orb}^2} = \frac{M_c \sin^3 i}{(1+q)^2} ,$$

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where $a_x \sin i$ is the semi-major axis of the neutron-star orbit, P_{orb} is the orbital period, M_c is the mass of the companion, i is the orbital inclination angle, and q is the ratio of the neutron-star mass to the companion mass. The orbits, and hence the mass functions, of 7 X-ray pulsars have now been measured in this manner (see Kelley, Rappaport, and Petre 1980 for references). For systems in which the optical companion can be identified, it may be possible to obtain the Doppler velocity of the companion, K_c, from spectral studies of strong photospheric absorption lines. This information can be combined with the parameters obtained from the X-ray observations to deduce the mass ratio q. Provided that the orbital inclination can also be determined, the neutron-star mass is obtained from the mass function.

If the source exhibits X-ray eclipses, it is possible to estimate the orbital inclination angle as follows. The photospheric radius of the companion star in units of the orbital separation (R_c/a) can be simply related, by geometry, to the inclination angle and the eclipse angle, θ_e. On the other hand, the size of the critical potential lobe in units of the orbital separation (R_L/a), which sets an upper limit to the size of the companion, depends only on q and the rotation rate of the companion star (see, e.g., Avni 1976; Rappaport 1979). Studies of the ellipsoidal light variations displayed by several X-ray binaries (see, e.g., Bahcall 1978) indicate that the companion stars nearly fill their critical potential lobes (i.e., $\beta \equiv R_c/R_L \gtrsim 0.9$; Avni and Bahcall 1975a,b). The rotation rates of the companion stars are known only approximately, but the ones that exhibit ellipsoidal light variations appear to have rotation rates that lie in the range $0 \lesssim \Omega \lesssim 1.5$, where $\Omega = P_{orb}/P_{rot}$ (see, e.g., Conti 1978). Furthermore, the effects of tidal dissipation in the companion star are expected to force these systems into approximately synchronous rotation (i.e., $\Omega \sim 1$; see, e.g., Lecar, Wheeler and McKee 1976).

With the above set of relations and assumptions, the orbital inclination can be estimated and the most probable neutron-star mass obtained. In practice, however, it is difficult to propagate the experimental uncertainties in $a_x \sin i$, K_c and θ_e, and the experimental and theoretical uncertainties in β and Ω. The probability distributions have therefore been calculated by a Monte Carlo technique (Rappaport, Joss and Stothers 1980) in which $a_x \sin i$, K_c, θ_e are chosen for each source from the appropriate experimental probability distributions, and β and Ω are chosen from uniform distributions in the ranges $0.9 \leq \beta \leq 1.0$ and $0 \leq \Omega \leq 1.5$. The resulting probability distributions for 4 neutron-star masses are shown in Figure 1a.

These distributions can be integrated to find the mass limits for a desired confidence level. In Figure 1b we show the 95% confidence limits for the 4 neutron-star masses determined in this way. The inner limits on the X-ray pulsar masses in Figure 1b were computed for the less conservative case where $\beta = \Omega = 1$, which corresponds to Roche geometry with the companion star filling its Roche lobe. Also shown are the mass limits for Her X-1 and the binary radio pulsar PSR1913+16, added for completeness.

For the Her X-1 system the high degree of X-ray heating of the companion star, HZ Her, has prevented a reliable determination of the companion's orbital velocity. However, studies of the optical pulsations, which are apparently due to the reprocessing of the X-ray pulsations that impinge on the photosphere of the companion, have resulted in a determination of the mass of Her X-1 (Middleditch and Nelson 1976; Bahcall and Chester 1977). The mass of PSR1913+16 has been obtained through the measurement of general relativistic effects in that binary system (Taylor, Fowler and McCulloch 1979; Taylor 1981).

The measured neutron-star masses in Figure 1b are consistent with the range of masses (shaded region in Fig. 1b) that might be expected if the neutron stars were formed during the collapse of the degenerate cores of highly evolved stars (Arnett and Schramm 1973; Iben 1974), or from the collapse of accreting degenerate dwarfs in close binary stellar systems (see, e.g., Canal and Schatzman 1976). The allowed range of neutron-star masses is consistent with, but does not yet significantly constrain, neutron-star models based on conventional many-body nuclear and high-energy physics (see, e.g., Arnett and Bowers 1977; Fechner and Joss 1978; and references therein).

In the future we anticipate that the discovery of more binary X-ray pulsar systems will significantly add to the statistical sample of neutron-star masses. Improved X-ray and optical measurements should further reduce the uncertainties in neutron-star masses by a factor of at least several over present results.

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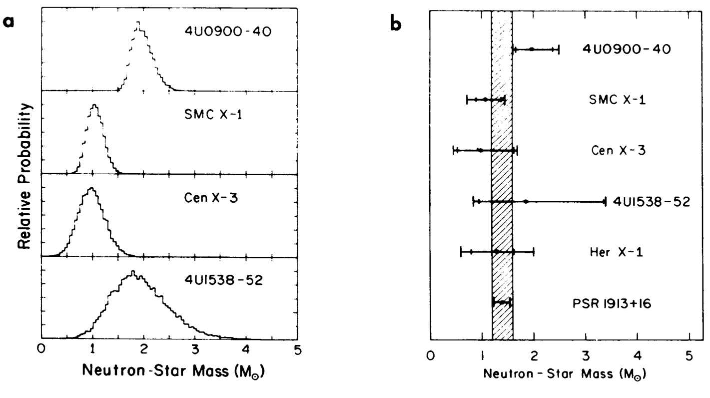

Fig. 1a) Probability distributions of the neutron-star masses for four binary X-ray pulsars. (b) Integrated 95% confidence limits on the masses of neutron stars (from Rappaport and Joss 1981). The mass of Her X-1 is from Bahcall and Chester (1977). The inner mass limits are for the special case where the companion fills its Roche lobe. The mass of the radio pulsar PSR1913+16 is from Taylor et al. (1979).

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