Neutron Star Mass Determinations

M. H. van Kerkwijk

Utrecht University, P. O. Box 80000, 3508 TA Utrecht, The Netherlands

Abstract. I review attempts made to determine the properties of neutron stars. The focus is on the maximum mass that a neutron star can have, or, conversely, the minimum mass required for the formation of a black hole. There appears to be only one neutron star for which there is strong evidence that its mass is above the canonical $1.4 M_\odot$, viz., Vela X-1, for which a mass close to $1.9 M_\odot$ is found. Prospects for progress appear brightest for studies of systems in which the neutron star should have accreted substantial amounts of matter.

1 The Minimum Mass Required to Form a Black Hole

For the study of black holes, the relevance of neutron stars is mostly that below a certain maximum mass, degeneracy pressure due to nucleons is sufficient to prevent an object from becoming a black hole. Unfortunately, the equation of state of matter at densities above nuclear-matter density is rather uncertain and theoretical estimates of the minimum mass required to form a black hole range from just over $1.4 M_\odot$ to about $2.5 M_\odot$ [3,10].

Constraints on the equation of state can be obtained from a variety of observed properties of neutron stars. Among the more direct measurements that have been used or proposed are: (i) the maximum mass inferred from dynamical measurements in binaries; (ii) the minimum spin period among millisecond pulsars; (iii) identification of kHz quasi-periodic oscillations with the orbital frequency in the last stable orbit; (iv) identification of quasi-periodic oscillations with the Lens-Thirring precession period; (v) influence of gravitational light bending on X-ray light curves in radio pulsars; (vi) model-atmosphere fitting of X-ray lightcurves during X-ray bursts (resulting from to thermonuclear run-aways on the neutron-star surface); (vii) gravitational redshift from $\gamma$-ray spallation lines in accreting systems; (viii) gravitational redshift and surface gravity from model-atmosphere analysis of spectra of isolated neutron stars. Less direct measurements include: (ix) matching observed neutron-star temperatures and inferred ages to cooling curves; (x) neutrino light curves in supernova explosions; (xi) pulsar glitches; (xii) moment of inertia from accretion torques in combination with knowledge of the magnetic field strength from cyclotron lines; (xiii) comparing X-ray fluxes between states in which a neutron star is accreting and in which matter is stopped at the magnetosphere and “propelled” away. For references and somewhat more detail, see [20]. The strongest constraints on the equation of state are still set by dynamical mass measurements, so I will restrict myself to those below.
2 Dynamical measurements

Most mass determinations have come from radio timing studies of pulsars; see [16] for an excellent review. The most accurate ones are for pulsars that are in eccentric, short-period orbits with other neutron stars, in which several non-Keplerian effects on the orbit can be observed: the advance of periastron, the combined effect of variations in the second-order Doppler shift and gravitational redshift, the shape and amplitude of the Shapiro delay curve shown by the pulse arrival times as the pulsar passes behind its companion, and the decay of the orbit due to the emission of gravitational waves. The most famous of the double neutron-star binaries is the Hulse-Taylor pulsar, PSR B1913+16, for which recent measurements give $M_{\text{PSR}} = 1.4411 \pm 0.0007 \, M_\odot$ and $M_{\text{comp}} = 1.3874 \pm 0.0007 \, M_\odot$ [14,13]. Almost as accurate masses have been inferred for PSR B1534+12, for which the pulsar and its companion are found to have very similar mass: for both, $M = 1.339 \pm 0.003 \, M_\odot$ [11].

Neutron-star masses can also be determined for some binaries containing an accreting X-ray pulsar, from the amplitudes of the X-ray pulse delay and optical radial-velocity curves in combination with constraints on the inclination (the latter usually from the duration of the X-ray eclipse, if present). This method has been applied to about half a dozen systems [6,8,18], but the masses are generally not very precise.

So far, for all but one of the neutron stars, the masses are consistent with being in a surprisingly narrow range, which can be approximated with a Gaussian distribution with a standard deviation of only 0.04 $M_\odot$ [16]. The mean of the distribution is 1.35 $M_\odot$, close to the “canonical” value of 1.4 $M_\odot$.

The one exception is the X-ray pulsar Vela X-1, which is in a 9-day orbit with the B0.5 Ib supergiant HD 77581. For this system, a rather higher mass of around 1.8 $M_\odot$ has consistently been found ever since the first detailed study in the late seventies [21,19]. A problem with this system is that the measured radial velocities show strong deviations from a pure Keplerian radial-velocity curve, which are correlated within one night, but not from one night to another. A possible cause could be that the varying tidal force exerted by the neutron star in its eccentric orbit excites high-order pulsation modes in the optical star which interfere constructively for short time intervals.

We were granted time at ESO to improve the mass determination of this possibly very massive neutron star from 200 new spectra, taken in as many nights. These cover more than 20 orbits, and make it possible to average out the velocity excursions and to constrain possible systematic effects with orbital phase. In combination with measurements from our old photographic plates, earlier CCD spectroscopy, and high resolution IUE spectra, one study based on IUE spectra of HD 77581 appeared to find a lower neutron-star mass [2]. However, this was found to be due to a bug in the cross-correlation software used [1].
Fig. 1. Constraints on the mass of Vela X-1 and its supergiant companion HD 77581 [1,2]. The constraint on the mass ratio from the X-ray pulse delay and optical radial-velocity curves is indicated by the solid line. The long and short-dashed lines next to it indicate the 95% and 99% confidence limits, respectively. The lines stop at the region excluded by the pulse-timing mass function (to go below it would require $\sin i > 1$). The 95% and 99% confidence lower limits on the inclination derived from the duration of the X-ray eclipse are indicated by the two dotted lines.

We derived a 95% confidence constraint on the mass of the neutron star of $M_{NS} = 1.87^{+0.23}_{-0.17}$ [1]. Our constraints are illustrated graphically in Fig. 1. One sees that even at 99% confidence, $M_{NS} > 1.6 M_\odot$. It should be noted, however, that from the data it appears that while the excursions in radial velocity are mostly random, there is also a component that is systematic, locked to orbital phase. Since we do not understand these effects, it may be that our mass estimate is biased. In our trials with excluding the worst-affected phase ranges, however, we consistently found that the fitted mass became even higher [13].

3 Trying for Bias

The narrow range in masses inferred for most neutron stars might be seen as evidence for a relatively low maximum neutron-star mass. It could also be,
however, that it reflects the formation mechanism. Indeed, from models, it appears that supernova explosions result in neutron stars with masses preferentially in two narrow peaks, one around $1.3 \, M_\odot$ and one around $1.65 \, M_\odot$.\cite{15} It is tempting to associate the latter with Vela X-1, but for honesty it should be noted that from the same calculations it is expected that only lighter neutron stars can be formed by stars which lose their envelope during their evolution, as would likely have happened for the progenitor of Vela X-1.

If the narrow range indeed reflects the formation process, it seems worthwhile to focus especially on systems in which the neutron star is expected to have accreted a lot of matter since it was formed. Such systems are the low-mass X-ray binaries and their descendents, the pulsars with low-mass white dwarf companions. In the latter systems, the white dwarfs typically have masses of $0.3 \, M_\odot$. However, in order for mass transfer to have happened, these stars need to have evolved to at least the end of the main sequence life. For this to happen in a Hubble time, their masses need to have been at least $0.8 \, M_\odot$ initially. Since the mass transfer in these systems is thought to be stable, the neutron star should thus have accreted more than $0.6 \, M_\odot$, i.e., have become substantially more massive than it was initially.

From radio timing measurements, it is generally more difficult to measure masses for these systems, because the orbits are circular and relatively wide. However, for one system, PSR B1855+09, the orbit is very close to edge on, and it has been possible to derive constraints from the Shapiro delay\cite{7,16}. These constraints are indicated in Fig. 2.

Another way of determining the masses in these systems uses optical spectroscopy of the white-dwarf companion. From a model-atmosphere fit to the spectrum, one can determine the effective temperature and surface gravity. From the latter, the white-dwarf mass follows, assuming a theoretical mass-radius relation. If one can also measure the radial-velocity orbit, and determine the mass ratio (in combination with the pulse-delay orbit), then one has a constraint on the neutron-star mass. So far, the only pulsar for which this has been possible is PSR J1012+5307\cite{17,4}, whose companion is particularly bright ($V \simeq 20$). The present constraints are shown in Fig. 3.

One sees that for both systems, the mass determinations are at present not precise enough to provide meaningful additional constraints on the maximum mass a neutron star can have. The situation unfortunately is no better for determinations in low-mass X-ray binaries. A problem for those is that the X-ray sources generally do not pulse, and hence all information has to be gleaned from observations of the companions. So far, a meaningful determination has been possible only for Cyg X-2\cite{5,9}. A relatively high mass is found, but again the uncertainties are rather large.

Despite the above, prospects for progress appear brightest for further studies of systems in which the neutron star should have accreted a substantial amount of matter. Some other white-dwarf companions are bright enough, and more may be found in the on-going pulsar searches.
Fig. 2. Constraints on the mass of PSR B1855+09 and its white-dwarf companion. The horizontal line is at the best fit white-dwarf mass derived from the amplitude of the Shapiro delay curve, and the short-dashed lines reflect the 95% confidence uncertainties on that measurement. The lines stop at the limit derived from the pulse timing mass function, at $i = 90^\circ$; to be to the right or below it would require $\sin i > 1$. The barely visible short-dashed curve just left of it reflects the 95% confidence lower limit on the inclination set by the shape of the observed Shapiro delay curve (the upper limit would not be visible in this graph).

References

1. Barziv O., Kaper L., Van Kerkwijk M. H., Telting J., Van Paradijs J., 2000, in preparation
2. Bildsten L., Chakrabartty D., Chiu J., et al., 1997, ApJS 113, 367
3. Datta, B., 1988, Fund. Cosmic Phys. 12, 151
4. Callanan P. J., Garnavich P. M., Koester, D., 1998, MNRAS 298, 211
5. Casares J., Charles P. A., Kuulkers E., 1997, ApJ 493, L39
6. Joss P. C., Rappaport S. A., 1984, ARA&A 22, 537
7. Kaspi V. M., Taylor J. H., Ryba M., 1994, ApJ 428, 713
8. Nagase F., 1989, PASJ 41, 1
9. Orosz J. A., Kuulkers E., 1999, MNRAS 305, 132
10. Srinivasan G., 2000, these proceedings
11. Stairs I. H., Arzoumanian Z., Camilo F., Lyne A. G., Nice D. J., Taylor J. H., Thorsett S. E., Wolszczan A., 1998, ApJ 505, 352
Fig. 3. Constraints on the mass of PSR J1012+5307 and its white-dwarf companion. The horizontal solid line reflects the white-dwarf mass inferred from the surface gravity measured from the optical spectrum of the white dwarf. The slanted solid line is the constraint set by the mass ratio inferred from the optical radial-velocity and radio pulse-delay curves. For both curves, the 95% confidence regions are indicated by the associated short-dashed lines. All lines stop at the limit derived from the pulse timing mass function, at $i = 90^\circ$; to be to the right or below it would require $\sin i > 1$. Dotted lines indicate the relations expected for some other values of the inclination.

12. Stickland D., Lloyd C., Radziun-Woodham A., 1997, MNRAS 286, L21
13. Taylor J. H., 1992, Phil. Trans. R. Soc. London A 341, 117
14. Taylor J. H., Weisberg J. M., 1989, ApJ 345, 434
15. Timmes F. X., Woosley S. E., Weaver Th. A., 1996, ApJ 457, 834
16. Thorsett S. E., Chakrabarty D., 1998, ApJ 512, 288
17. Van Kerkwijk M. H., Bergeron P., Kulkarni S. R., 1996, ApJ 467, L89
18. Van Kerkwijk, M. H., Van Paradijs J., Zuiderwijk, E. J., 1995, A&A 303, 497
19. Van Kerkwijk M. H., Van Paradijs J., Zuiderwijk E. J., Hammerschlag-Hensberge G., Kaper L., Sterken C., 1995, A&A 303, 483
20. Van Paradijs J., 1998, in Buccheri R., Van Paradijs J., Alpar M. A. (eds), The Many Faces of Neutron Stars. Kluwer Academic Publishers, Dordrecht, 279 (astro-ph/9802177)
21. Van Paradijs J., Zuiderwijk E. J., Takens R., Hammerschlag-Hensberge G., Van den Heuvel E.P.J., De Loore C., 1977, A&AS 30, 195