PROPERTIES OF NEUTRON STARS

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I review attempts made to determine the properties of neutron stars. I focus on
constraints on the maximum mass that a neutron star can have, and on attempts
to measure neutron-star radii. So far, 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. While for individual systems the evidence that
neutron stars can have high masses is weak, the ensemble appears to show that
masses around 1.6 $M_\odot$ are possible. For the radius determination, most attempts
have focussed on neutron stars in low-mass X-ray binaries in which accretion has
temporarily shut down. These neutron stars are easiest to model, since they should
have pure Hydrogen atmospheres and low magnetic fields. To obtain accurate radii,
however, requires precise distances and very high quality data.

1. Trying to constrain the equation of state

The physics of matter at ultra-high density is not only of interest on its
own accord, but also because of its astronomical implications: to under-
stand the core collapse of massive stars, the supernova phenomenon, and
the existence and properties of neutron stars, knowledge of the physics,
as summarised in the equation of state (EOS), is required. As is clear
from other contributions to these proceedings, quantum-chromodynamics
calculations are not yet developed well enough to determine the densities
at which, e.g., meson condensation and the transition between the hadron
and quark-gluon phases occur. At densities slightly higher than nuclear
and at high temperatures, the model predictions can be compared with the
results of heavy-nuclei collision experiments. The substantial progress on
this front is discussed elsewhere in these proceedings. For higher densities
and low temperatures, however, no terrestrial experiments seem possible;
the models can be compared only with neutron-star parameters. Recent
reviews of our knowledge of the EOS, and the use of neutron stars for con-
straining it, are given by Heiselberg & Pandharipande\textsuperscript{11}, and Lattimer & 
Prakash.\textsuperscript{15,16}

Here, I focus on two possible ways to constrain the EOS: aiming to fin-
d the highest observed neutron-star mass, and to measure precise radii. The 
first part is an update of reviews I have given earlier.\textsuperscript{31,32}

2. Maximum mass

Observationally, after spin periods, masses are perhaps the easiest bulk 
properties to determine. Their possible interest for constraining the EOS is 
that for any given EOS, there is a maximum mass a neutron star can have; 
beyond this, it would collapse to a black hole. For instance, for EOS with a 
phase transition at high densities, such as Kaon condensation,\textsuperscript{5} only neutron 
stars with mass $< 1.5 M_\odot$ could exist. This EOS would be excluded if a 
neutron star with a mass above this maximum were known to exist. Below, 
I first describe the constraints given by the very accurate masses derived 
from relativistic binary neutron stars, and next the less precise masses from 
X-ray binaries. I then discuss whether the narrow mass range implied by the 
most accurate masses implies a constraint on the EOS, or rather reflects 
the astrophysical processes by which neutron stars form. I conclude by 
briefly describing the situation for neutron stars for which on astronomical 
grounds one might expect that they have accreted a substantial amount, 
and hence have become more massive.

2.1. Relativistic neutron-star binaries

The most accurate mass determinations have come from radio timing stud-
ies of pulsars (see Thorsett & Chakrabarty\textsuperscript{29} for an excellent review). The 
best among these 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 $M_{\text{PSR}} = 
1.4411 \pm 0.0007 M_\odot$ and $M_{\text{comp}} = 1.3874 \pm 0.0007 M_\odot$ was derived.\textsuperscript{28,27} Almost 
as accurate masses have been inferred for PSR B1534+12, for which 
the pulsar and its companion were found to have very similar mass;\textsuperscript{26}
$M_{\text{PSR}} = 1.3332 \pm 0.0010\ M_\odot$ and $M_{\text{comp}} = 1.3452 \pm 0.0010\ M_\odot$.

To these two best-known systems, recently two further interesting binaries have been added. The first is PSR J1141–6545, for which $M_{\text{PSR}} = 1.30 \pm 0.02\ M_\odot$ and $M_{\text{comp}} = 0.99 \pm 0.02\ M_\odot$ was measured; here, the companion is most likely a massive white dwarf. Very recently (after the conference), the discovery of a neutron-star binary was announced in which both components are radio pulsars. From this ‘double-lined’ radio pulsar binary, masses $M_{\text{PSR,1}} = 1.337 \pm 0.005\ M_\odot$ and $M_{\text{PSR,2}} = 1.250 \pm 0.005\ M_\odot$ were derived.

From the above, one sees that all these well-determined masses are in a relatively narrow range, between 1.25 and 1.44 $M_\odot$.

### 2.2. The high-mass X-ray binary Vela X-1

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. The masses are generally not very precise, but are consistent with $\sim 1.4\ M_\odot$ in all but one case.

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. A problem with this system, however, is that the measured radial-velocity orbit, on which the mass determination relies, shows strong deviations from a pure Keplerian radial-velocity curve. These deviations are correlated within one night, but not over longer periods. 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.

The velocity excursions appeared not to depend on orbital phase, and we hoped that, with sufficient observations, it would be possible to average

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*aGiven that this system has an eccentric orbit, it seems certain that the white dwarf was formed before the supernova explosion that left the neutron star (and made the orbit eccentric). Likely, what happened is that both stars in the binary originally had masses too low to form a neutron star, but that as the originally more massive star evolved, a phase of mass transfer ensued in which the originally less massive star received sufficient material to push its mass over the limit required for neutron-star formation (for references, see citations in Bailes et al.1)."
Figure 1. Radial-velocity measurements for HD 77581, the optical counterpart to Vela X-1. Overdrawn is the Keplerian curve that best fits the nightly averages of the data (solid line; $K_{\text{opt}} = 21.7 \pm 1.6 \text{ km s}^{-1}$), as well as the curve expected if the neutron star has a mass of $1.4 M_{\odot}$ (dotted line; $K_{\text{opt}} = 17.5 \text{ km s}^{-1}$). The residuals to the best-fit are shown in the middle panel. For clarity, the error bars have been omitted. Points taken within one night are connected with lines. In the bottom panel, the residuals averaged in 9 phase bins are shown. The horizontal error bars indicate the size of the phase bins, and the vertical ones the error in the mean. The dotted line indicates the residuals expected for a $1.4 M_{\odot}$ neutron star.

them out. For that purpose, we obtained about 150 spectra, taken in as many nights and covering more than 20 orbits, of the optical counterpart. Unfortunately, we found that the average velocity curve does show systematic effects with orbital phase (see Fig. 1), which dominate our final uncertainty. While our best estimate still gives a high mass, of $1.86 M_{\odot}$, the $2\sigma$ uncertainty of $0.33 M_{\odot}$ does not allow us to exclude soft equations of state conclusively.

A different approach would be to try to obtain very dense coverage of
the orbit, in the hope that one could model and remove the excursions. This approach was tried too,\textsuperscript{21} and for the two weeks covered by the observations, it was found to be possible to model the velocity excursions as a fairly coherent, 2.18-d oscillation (in contrast to what was the case in earlier observations\textsuperscript{35}). After removal, however, the systematic orbital-phase dependent effects that plagued our determination became apparent here too, and the final mass has roughly the same value, but also roughly the same uncertainty as the one described above.

\subsection*{2.3. Physical or astrophysical implications?}

While we cannot draw a firm conclusion about the mass of Vela X-1, it is worth wondering how it could be the only neutron star with a mass so different from all others. I would argue one should be careful in taking the narrow mass range around $1.4 \, M_\odot$ as evidence for an upper mass limit set by the EOS.\textsuperscript{2} After all, for all EOS, neutron stars substantially less massive than $1.4 \, M_\odot$ can exist, yet none are known. Could it be that the narrow range in mass simply reflects the formation mechanism, i.e., the physics of supernova explosions and the evolution of stars massive enough to reach core collapse? There certainly is precedent: white dwarfs are formed with masses mostly within a very narrow range around $0.6 \, M_\odot$, well below their maximum (Chandrasekhar) mass.

Interestingly, from evolutionary calculations,\textsuperscript{30} it is expected that single stars produce neutron stars with a bimodal mass distribution, with peaks at 1.27 and 1.76 $M_\odot$. For stars in binaries, only a single peak at $\sim 1.3 \, M_\odot$ was found, but it is not clear whether this result will hold (S. Woosley, 2000, pers. communication). If not, could it be that the progenitor of Vela X-1 was a star that managed to produce a massive neutron star? If so, one may still wonder why no massive radio pulsars or pulsar companions have been found. This may be a selection effect:\textsuperscript{2} all neutron stars with accurate masses are in binary neutron stars systems in close orbits, whose formation requires a common-envelope stage. During this stage, a merger can only be avoided if the initial orbit was very wide. Stars massive enough to form a massive neutron star, however, likely do not evolve through a red-giant phase, and a common-envelope phase would occur only for rather close orbits, for which the binary would merge.
2.4. Trying for bias

In considering the mass measurements discussed above, it should be noticed that for all neutron stars with good masses, it is expected that they accreted only little mass after their formation. Only neutron stars in low-mass X-ray binaries and radio pulsars with low-mass white dwarf companions are expected to have accreted substantial amounts of material. It may thus be worthwhile to try to bias oneself to more massive neutron stars by studying these.

For low-mass X-ray binaries, higher masses, of $\sim 2M_\odot$, have indeed been suggested; e.g., from dynamical measurements and lightcurve fitting for Cyg X-2, and from inferences based on quasi-periodic oscillations. These estimates, however, rely to greater or lesser extent on unproven assumptions.

The radio pulsars with white dwarf companions provide cleaner systems, for a number of reasons. First, most of the radio pulsars in these binaries spin very rapidly and stably, making them ideally suited for precision timing. Second, both components can safely be approximated as point masses for dynamical purposes, so that deviations from Keplerian motion can be readily interpreted. Third, by taking optical spectra of the white dwarf, it is possible to determine its radial-velocity curve, and thus obtain the mass ratio. Finally, from a model-atmosphere analysis of optical spectra, one can infer the surface gravity and, using the white-dwarf mass-radius relation, the mass. Combined with a mass ratio, this yields the pulsar mass.

In many of these systems, one expects the neutron star to have accreted a substantial amount of matter. This is because many of the white dwarf companions have masses of only $\sim 0.2M_\odot$. In order for their progenitors to have evolved off the main sequence in a Hubble time, the initial masses much have been at least $0.8M_\odot$. Hence, at least $0.6M_\odot$ was lost. From evolutionary considerations, one would expect much of this to have been accreted to the neutron star, as mass transfer should have been relatively slow and stable.

Despite the above expectations, initial results showed no evidence for such high masses. Current results for four systems are shown in Fig. 2. One sees that for none of these, the mass measurements exclude $1.4M_\odot$ at high significance, but for all the best values are above it. This is true for a number of other systems as well.

While the masses appear to be above the narrow range inferred from the relativistic binary pulsars, suggesting that some accretion has happened,
Figure 2. Constraints on the masses of four radio pulsars with white-dwarf companions. In all panels, the solid line with hashing on the lower right reflects the limit set by the pulsar mass function. The horizontal lines reflect the limits on the companion mass, with the 2-σ uncertainties. For PSR J1012+5307, the mass is inferred from a fit to the optical spectrum, while for the other three sources it is measured from Shapiro delay. The Shapiro delay also implies inclinations very close to 90° (edge-on) for PSR B1855+09 and PSR J1909−3744. For PSR J0437−4715, the curved line is the constraint on the inclination, inferred from the change in aspect with which we view the system due to its proper motion. For PSR J1012+5307, the diagonal straight lines show the mass ratio and its 2-σ uncertainties, inferred from the radial-velocity amplitudes of the two components. The vertical lines show the resulting 2-σ constraints on the pulsar masses.

the masses are not as high as the expected $\sim 2 M_\odot$. Could this reflect a hard limit set by the EOS? Unfortunately, there may also be a more mundane, astronomical explanation. The pulsars in these binaries have magnetic fields that are much weaker than those inferred for regular radio pulsars. On empirical grounds, it is believed this reduction is related to being in a binary, with the magnetic field being reduced somehow by the
accretion (for a review, see Phinney & Kulkarni). If this is indeed the case, above some amount of accreted matter, the magnetic field may be reduced so far that no pulsar will be seen. This would thus lead one to find a upper limit to the mass of pulsars that accreted matter.

Even though the above may mean a low apparent upper limit to the mass distribution may not be very meaningful, the masses do appear to be higher than in other systems. At present, therefore, the radio pulsars with white dwarf companions still seem to be the most promising systems for obtaining precise and reliable masses that provide strong constraints on the EOS. Further radio timing observations, as well as optical spectroscopy, are underway.

3. Atmospheric modelling

Spectroscopic analysis of emission arising in the photosphere of a neutron star offers, in principle, the possibility of much stronger constraints. From models, the temperature and angular diameter could be inferred, which, combined with a distance, gives the radius. If absorption lines are present, also the gravitational redshift \( \Rightarrow M/R \) and pressure broadening \( \Rightarrow M/R^2 \) can be measured. An accurate measurement of even just one of these may be useful, given the narrow range of observed neutron-star masses for neutron stars that did not accrete much after their formation.

In practice, most neutron stars are unsuitable: many have spectra contaminated or even dominated by poorly understood magnetospheric or accretion processes. Even without those, the strong magnetic fields present in many neutron stars imply that the microphysics (energy levels, radiative transfer, etc.) is complicated and that the temperature will in general not be uniform. Finally, most have atmospheres almost certainly composed of pure Hydrogen, since, if any is present, gravitational settling ensures that it will quickly float to the top.

3.1. Quiescent emission from low-mass X-ray binaries

The only neutron stars for which no pulsations are seen, and which therefore may not have significant magnetic fields, are those that reside in low-mass X-ray binaries. For some of these, the accretion is episodic, and when accretion turns off, one may be able to observe simple thermal emission from the surface.

Given that the accreted matter contained Hydrogen, which will float to the top, the atmosphere should be composed of pure Hydrogen. This makes
the modelling relatively easy, even if it also implies likely no lines will be seen (small features may be visible due to continuing low-level accretion). Thus, the best one can hope for is to determine effective temperatures and angular diameters. If one has a distance, e.g., because the source is in a globular cluster, this will yield the radius. This may even be quite precise, as distances to globular clusters are becoming better and better.

A possible problem lies in the interpretation: one measures the radius as seen at infinity, $R_\infty = R/\sqrt{1 - 2GM/Rc^2}$, which, unfortunately, depends more strongly on the precise value of the mass than the radius itself. Since accretion has happened, one does not know the mass a priori. Nevertheless, significant constraints are possible. For instance, for many soft EOS, one finds $R_\infty < 14\text{ km}$ for neutron stars with any mass between 0.5 and the upper limit for those EOS, $\sim 1.6M_\odot$. Similarly, for the stiffer EOS, one finds $R_\infty > 15\text{ km}$ for any mass above $1.35 M_\odot$.

Attempts to measure radii for neutron stars in low-mass X-ray binaries in quiescence have been made by a number of authors. Most work has been done for binaries in the field.\textsuperscript{6,22,23,25,39} For these, one will need to obtain parallaxes to obtain meaningful radii. However, the observations also showed that the interpretation was not always as straightforward as hoped. First, for some sources, interstellar absorption cuts off a large part of the spectrum, making it difficult to measure the temperature accurately. Second, in the best studied source, Aql X-1, a non-thermal component was found, and even the thermal component was found to be variable on a relatively short timescale of months.\textsuperscript{24} These complications shed some doubt on whether the observations are interpreted correctly. It also gives some hope, however: the non-thermal emission is likely due to residual accretion, and it may be possible to see the signature of that in lines from heavier elements.

More recently, the focus has shifted to sources in globular clusters, where the distances are known to fair precision. The best results have come from XMM, because of its large collecting area.\textsuperscript{9,10} For the two sources studied in most detail, the uncertainty in the radius now seems dominated by the uncertainty in the distance; the uncertainty due to just the X-ray fitting appears to be below 0.5 km.

3.2. **X-ray bursts**

The X-ray emission of low-mass X-ray binaries is dominated by emission from the neutron-star surface not only in quiescence, when accretion is ab-
sent, but also during so-called X-ray bursts. These X-ray bursts occur when
the layer of freshly accreted matter becomes unstable to nuclear burning
(usually of Helium; Hydrogen is burnt at least partially as matter accretes;
for a review, see Bildsten\textsuperscript{3}). The bursts typically last a few seconds, and
occur every few hours.

In a very long, 335 ks \textit{XMM} observation of the X-ray burst source
EXO 0748−676, taken for calibration purposes, 28 X-ray bursts were ob-
served. By analysing the summed spectra obtained during these bursts
(which lasted a cumulative 3.2 ks), possible small absorption features were
found, which could be identified with the \( n = 2 \) to 3 transition of Hydrogen-
and Helium-like Iron,\textsuperscript{8} for a gravitational redshift \( z = 0.35 \). It is not clear
where the Iron originates. One might think it results from the nuclear fu-
sion, and is brought to the surface, but an alternative explanation is that the
metals observed are brought to the photosphere by continuing accretion.\textsuperscript{4}

Unfortunately, while the results are extremely intriguing, they are very
difficult to confirm, since observationally it is hard to get much higher
quality data.

4. Conclusions and prospects

The pessimistic conclusion from the above would be that, since their discov-
ery, neutron stars have not much advanced our understanding of the physics
at extreme densities. Viewing the situation more positively, though, one
sees that the mass determinations are now getting accurate enough to be
interesting, especially for the radio pulsars with white dwarf companions.
The precision will increase with further timing of the pulsars, helped by
optical studies of the white dwarfs.

Furthermore, new avenues are explored in which the thermal emission
is modelled and used to derive angular diameters and gravitational red-
shifts. The study of low-mass X-ray binaries in quiescence seems particu-
larly promising, particularly once the distances settle down. For globular
clusters, this is in progress, while for individual systems in the field it will
come in the somewhat longer run, using direct parallax determinations with
NASA’s Space Interferometry Mission or ESA’s GAIA, both expected to
be launched in about ten years.

Finally, not mentioned in my talk or this write-up, there are a number
of nearby neutron stars with what appear to be purely thermal spectra.
Recently, for a number of these, absorption features have been detected,
which are likely due to Hydrogen atmospheres in extremely strong magnetic
fields, $10^{13}$ to $10^{14}$ G.\textsuperscript{34} In such fields, absorption might be due to proton cyclotron or neutral Hydrogen; with more than a single line, one may be able to solve for the field strength and the gravitational redshift. Several are close enough for parallax determinations; combined with angular diameters from atmospheric modelling, this might yield good radii.

Overall, the outlook seems fairly bright.

References

1. Bailes, M., Ord, S. M., Knight, H. S., & Hotan, A. W. 2003, Astroph. J. \textbf{595}, L49
2. Barziv, O., Kaper, L., van Kerkwijk, M. H., Telting, J., van Paradijs, J., 2001, Astron. Astroph. \textbf{377}, 925
3. Bildsten, L. 2000. In: Holt, S. S., & Zhang, W. W. (Eds) Cosmic Explosions, AIP, 359 (astro-ph/0001135)
4. Bildsten, L., Chang, P., & Paerels, F. 2003, Astroph. J. \textbf{591}, L29
5. Brown, G. E., & Bethe, H. A. 1994, Astron. J. \textbf{423}, 659
6. Brown, E. F., Bildsten, L., & Rutledge, R. E. 1998, Astroph. J. \textbf{504}, L95
7. Callanan, P. J., Garnavich, P. M., & Koester, D. 1998, Mon. Not. R. Astron. Soc. \textbf{298}, 211
8. Cottam, J., Paerels, F., & Mendez, M. 2002, Nature \textbf{420}, 51
9. Gendre, B., Barret, D., & Webb, N. A. 2003a, Astron. Astroph. \textbf{400}, 521
10. Gendre, B., Barret, D., & Webb, N. 2003b, Astron. Astroph. \textbf{403}, L11
11. Heiselberg, H., & Pandharipande, V. 2000, Ann. Rev. Nucl. & Part. Sci. \textbf{50}, 481
12. Jacoby, B. A., Bailes, M., van Kerkwijk, M. H., Ord, S., Hotan, A., Kulkarni, S. R., & Anderson, S. B. 2003, Astroph. J. \textbf{599}, L90
13. Joss, P. C., & Rappaport, S. A. 1984, Ann. Rev. Astron. Astroph. \textbf{22}, 537
14. Kaspi, V. M., Taylor, J. H., & Ryba, M. 1994, Astroph. J. \textbf{428}, 713
15. Lattimer, J. M., & Prakash, M. 2000, Phys. Rep. \textbf{333}, 121
16. Lattimer, J. M., & Prakash, M. 2001, Astroph. J. \textbf{550}, 426
17. Lyne, A. G., et al. 2004, Science \textbf{303}, 1153
18. Nice, D. J., Splaver, E. M., & Stairs, I. H. 2003. To appear in: Camilo, F., & Gaensler, B. M. (eds), Proc. IAU Symp. 218, ASP Conf. Proc., in press (astro-ph/0311296)
19. Orosz, J. A., & Kuulkers, E. 1999, Mon. Not. R. Astron. Soc. \textbf{305}, 1320
25. Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., Zavlin, V. E., & Ushomirsky, G. 2002b, Astroph. J. **580**, 413
26. Stairs, I. H., Thorsett, S. E., Taylor, J. H., & Wolszczan, A. 2002, Astroph. J. **581**, 501
27. Taylor, J. H. 1992, Phil. Trans. R. Soc. London A **341**, 117
28. Taylor, J. H., & Weisberg, J. M. 1989, Astroph. J. **345**, 434
29. Thorsett, S. E., & Chakrabarty, D., 1999, Astroph. J. **512**, 288
30. Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1996, Astroph. J. **457**, 834
31. Van Kerkwijk, M.H., 2001a. In: Kaper, L., Van den Heuvel, E.P.J., & Woudt, P.A. (eds.) Proc. of the ESO Workshop “Black holes in binaries and galactic nuclei.” Springer, Heidelberg (Germany), p. 39 (astro-ph/0001077)
32. Van Kerkwijk, M.H., 2001b. To appear in: Van den Heuvel, E.P.J., Kaper, L., & Rol, E. (eds), Proc. Jan van Paradijs Memorial Symposium. Astronomical Society of the Pacific, San Francisco (astro-ph/0110336)
33. Van Kerkwijk, M. H., Bergeron, P., & Kulkarni, S. R. 1996, Astroph. J. **467**, L89
34. Van Kerkwijk, M.H., Kaplan, D.L., Durant, M., Kulkarni, S.R., & Paerels, F., 2004, Astroph. J., accepted (astro-ph/0402418)
35. Van Kerkwijk, M. H., van Paradijs, J., Zuiderwijk, E. J., Hammerschlag-Hensberge, G., Kaper, L., & Sterken, C. S. 1995, Astron. Astroph. **303**, 483
36. Van Kerkwijk, M.H., van Paradijs, J., & Zuiderwijk, E.J. 1995, Astron. Astroph. **303**, 497
37. Van Paradijs, J., Zuiderwijk, E. J., Takens, R., Hammerschlag-Hensberge, G., Van den Heuvel, E. P. J., & De Loore C. 1977, Astron. Astroph. Supp. **30**, 195
38. Van Straten, W., Bailes, M., Britton, M., Kulkarni, S. R., Anderson, S. B., Manchester, R. N., & Sarkissian, J. 2001, Nature **412**, 158
39. Wijnands, R., Guainazzi, M., van der Klis, M., & Méndez, M. 2002, Astroph. J. **573**, L45
40. Zhang, W., Strohmayer, T. E., & Swank, J. H. 1997, Astroph. J. **482**, L167