Quasi-periodic Oscillations in Low-mass X-ray Binaries and Constraints on the Equation of State of Neutron Star Matter

Ch. Schaab and M. K. Weigel

Recently discovered quasi periodic oscillations in the X-ray brightness of low mass X-ray binaries are used to derive constraints on the mass of the neutron star component and the equation of state of neutron star matter.

In this investigation we derived models of rapidly rotating neutron stars and strange stars by solving the general relativistic structure equations for a broad collection of modern EOSs. We compared the space time geometry of these models with recently discovered QPOs in the X-raybrightness of LMXBs.

If one follows the general beat-frequency interpretation of the kilohertz-QPOs, i.e. that the higher frequency QPO originates at a stable circular orbit, one can constrain the mass of the neutron star to a range which depends on the EOS. This mass range is for all sources and for all EOSs consistent with a canonical mass, $M = 1.4\,M_\odot$. As it was stated by Miller et al. and Thampan et al. the exact lower and upper limits of the neutron star's mass can only be determined by using fully relativistic models of rapidly rotating neutron stars. The exact limits differ from the approximations with $j = 0$ by roughly 10 %.

As it was shown by Kaaret et al. and Zhang et al., the observation of a maximum frequency $\nu^{\max}_{\rm QPO1}$ of the high frequency QPO in the sources 4U 1820-30, 4U 1608-52, and 4U 1636-536 favour the interpretation that this QPO originates at the innermost stable orbit. If this interpretation is correct, the mass of the neutron star can be exactly (within the observational errors) determined for a given EOS. The approximately obtained mass, $M = 2.07\,M_\odot$, of the source 4U 1820-30 is larger than the maximum mass of most of the considered EOSs. This conclusion is even strengthened if the observed maximum frequency $\nu^{\max}_{\rm QPO1}$ is compared with the exact neutron star models. The only allowed EOSs of our broad collection are then the UV_{14}+UVII and RHF_{pn}, which both describe neutron star matter as consisting of nucleons and leptons only. The derived masses of the three sources lie in the narrow range between $M = 1.92\,M_\odot$ and $2.25\,M_\odot$.

This result is also of some importance for the nature of the object left in the supernova 1987A. During the first ten seconds after the supernova, neutrinos were detected. This means that a protoneutron star was formed in the supernova. The fact that up to now no pulsar emission could be detected was interpreted by Bethe & Brown that the protoneutron star collapsed to a black hole when the star became transparent to neutrinos after roughly 10 s. The estimated value of the baryonic mass $M_B \sim 1.63 - 1.76\,M_\odot$ (Bethe & Brown, 1995; Thielemann et al., 1996) gives thus an upper limit to the maximum gravitational mass of a neutron star: $M_{\max} \lesssim 1.6\,M_\odot$. This limit is in clear contradiction to the derived mass of, e.g. 4U 1820-30.

It is generally believed that neutron stars are born with a mass about $1.4 - 1.5\,M_\odot$. Neutron stars in LMXBs would therefore accrete $0.4 - 0.8\,M_\odot$ during their lifetime. It seems reasonable to assume that some of the neutron stars in LMXBs accrete enough matter to reach the maximally stable mass ($M_{\max} = 2.20\,M_\odot$ for UV_{14}+UVII, $M_{\max} = 2.44\,M_\odot$ for $\mathrm{RHF}_{\rm pn}$). The neutron star would then collapse to a black hole.

The interpretation of the QPO with frequencies $\nu_{\rm QPO3}$ about 10 Hz as Lense-Thirring precession frequency of the accretion disk seems not to be consistent with the theoretical star models, unless one assumes that the first overtone of the precession is observed. In the case of Z-sources however, the necessary ratio of the frame dragging frequency and spin frequency, and thus the moment of inertia, of the models is too small compared to the observed frequency $\nu_{\rm QPO3}$ or half of it.

Our general conclusion is that the observations of kilohertz QPOs in LMXPs provide us another powerful tool for probing the interior of neutron stars. Compared to the other tools like observations of the maximum mass, the limiting spin period, and cooling simulations, the derived constraints, especially in the sonic-point-interpretation, are rather strong. The lower limit $M_{\max} \gtrsim 2.15\,M_\odot$ is only consistent with two EOSs, UV_{14}+UVII and $\mathrm{RHF}_{\rm pn}$, which are relatively stiff at high densities. Their stiff behaviour at high densities seems to be only possible if the neutron star matter consists of neutrons, protons, and leptons only. At the most , a small admixture of hyperons may be allowed. However, one has to admit that such a composition somehow contradicts our conception of neutron star matter, since fieldtheoretical models lead more or less inevitably to a more complex composition at high density. If the given interpretation is correct, one has therefore to reinvestigate the problem of superdense neutron star matter by dropping, for instance, the standard assumptions about the coupling of the hyperons in such regimes.

This specific conclusion depends however on the interpretation of the maximum frequency of the kilohertz QPO within the sonic-point-model. As a kind of beat-frequency model, this model predicts a constant frequency separation $\Delta\nu = \nu_{\rm QPO1} - \nu_{\rm QPO2}$. Recently two further examples, where this constancy is not observed, has been discovered: 4U 1608-52 and 4U 1735-44. Moreover, the frequency separation in the Atoll source 4U 1636-536 seems not to be consistent with the half of the frequency of the QPO in type I bursts. Though the beat-frequency models are the most hopeful candidates in explaining the QPO-phenomenology it has to be awaited how the variation of the frequency separation and deviation from the QPO frequency in bursts can be incorporated in these models.

Published in: Mon. Not. Roy. Astron. Soc. **308** (1999) 718