Constraining the Equation of State of neutron stars from X-ray observations

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Introduction

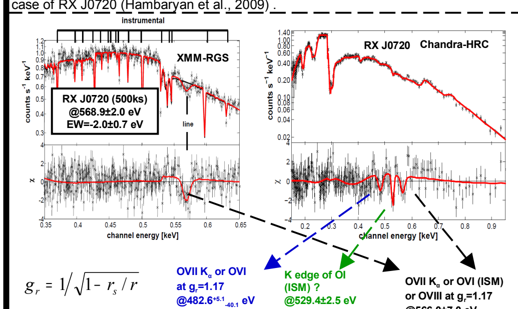
Matter at high pressure and densities (10^{15} g/cm³), large magnetic fields (10^{13} G) and high temperatures (10^6 K) cannot be generated in laboratories. To study the properties of matter under such extreme conditions, in particular the equation of state (EoS) at super nuclear densities, one needs suitable objects, hence neutron stars (NSs). The EoS can be constrained by the mass-radius relation (the compactness), period and long term evolution of the period (glitch, free precession) and cooling behaviour. Current NS models deal with various families of EoS, i.e. with strange stars (quark stars or stars with pion and/or kaon condensates), NSs with ordinary neutrons mixed with protons and electrons (stiff EoSs yielding larger radii and soft EoSs yielding smaller radii; both in conjunction with or without superfluid matter). It is not known which of the 70-100 different EoSs (see Lattimer, 2010 for a review) is realised in nature.

Suitable targets for such investigations are the so-called “Magnificent Seven” (M7), a group of young, isolated X-ray pulsars with large magnetic fields, that are radio-quiet and nearby (Haberl, 2007) with blackbody emission and the “Three Musketeers” (3M), that emit as one or two blackbodies in the X-ray with a power-law tail at higher energies (de Luca et al., 2005) and are known as radio sources.

Here, we present current results from X-ray spectroscopy and X-ray timing (XMM, Chandra and ROSAT) to constrain the EoS together with optical observations using HST (parallax measurements) and VLT-FORS (magnitude determination). Using Monte-Carlo simulations, we determined the kinematic age of some M7 and 3M, that can be used to understand the cooling process (that depends on the EoS too). Altogether, our results point to a stiff EoS with R_∞=17 km, in particular we can exclude quark stars.

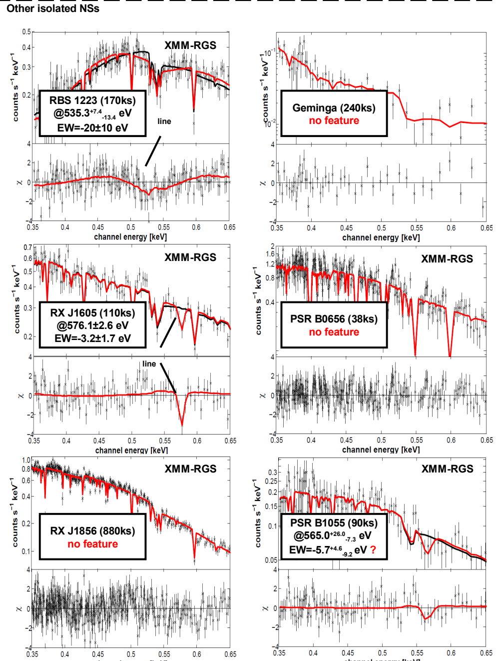
Compactness from spectral lines

Due to gravity, spectral lines appear redshifted, hence offer us the opportunity to measure the compactness. We (Hambaryan et al., 2009) found an absorption feature at 569 eV in the co-added RGS spectra of the M7 RX J0720, that would either fit to the Kα lines of He-like oxygen (OVII), mixed with absorption lines from OVI at rest (ISM), or to the Lyα line of OVIII with a grav. redshift g_r=1.17. Then, OVII would appear at 480 eV with the same redshift. Maybe such a line is found in the co-added HRC spectra of RX J0720 (Hohle et al., submitted). Van Kerkwijk et al. (2004) found a similar feature at 576 eV in the co-added RGS spectra of RX J1605, that could be confirmed by us. The features in the spectra of both NSs would fit to the different transitions of OVII at rest (1s2p^{1}P$_1$@573.95 eV and 1s2p^{3}P$_{1,2}$@568.63 eV), however only the resonance transition should be appear in absorption (alternatively, these lines are caused by redshifted OVIII Lyα absorption with slightly different compactness). We investigated the spectra of the other M7 and 3M (see below and Hohle et al, submitted) – some NSs exihbit these lines, whereas in some cases these lines are absent. Currently it is not known whether the absorption features are caused by the ISM, a circumstellar cloud/disk or from the NS atmosphere. A cloud/disk would account for some properties of the so-called optical excess in the case of RX J0720 (Hambaryan et al., 2009) .



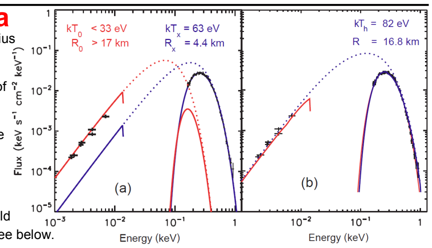
lines from the neutron star, circumstellar, or ISM?

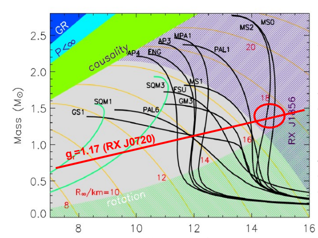
Other isolated NSs



Radius from optical and X-ray data

Using the modified Stefan-Boltzmann law, it is possible to derive the radius of a NS, if temperature and distance is known. The temperature can be measured from X-ray observations (XMM/Chandra), whereas the determination of the distance is challenging. We determined updated values of the parallaxes of the two M7 RX J1856 (Walter et al., 2010) and RX J0720 (Eisenbeiß, 2011) using HST observations, yielding distances of 122±11 pc and 278$^{+210}_{-84}$ pc, respectively. The X-ray spectra deliver the size of the emitting area, i.e. the hot spots (not the NS radius). Together with the optical magnitudes (~25-27 mag; emission from the cooler regions of the NS), we used a two component model with different temperature profiles (figure on the right) to determine the radius (see table on the right). Most likely the radii have values of R_∞ around 17 km, that would obey a stiff EoS, see below.





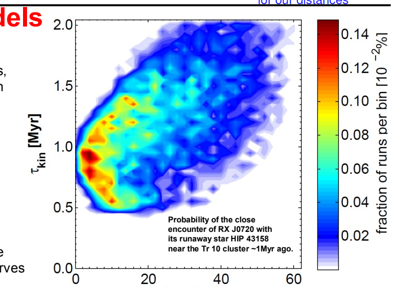
Left: M/R diagram taken from Lattimer (2010). The up right shaded region marks the part of the diagram that would host valid EoS (black curves) from the radius determination of RX J1856, obtained from recent parallax measurements (table on the right). We also show a red line indicating the compactness (M/R [M_{SUN}/km]=0.0907) derived from the possible grav. redshifted (g_r=1.17) absorption lines in the spectra of RX J0720. Both, the red line and the shaded area intersect with two stiff EoS, namely MS2 (Müller & Serot, 1996) and MS0 (Müller & Serot, 1995). From our observations we can likely exclude the EoS for quark stars (SQM1 and SQM3)

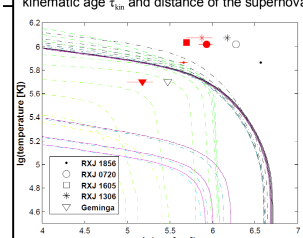
RX	R^∞ [km]	$R(1.4\,M_\odot)$ [km]
J0720	$d = 280$ pc	
	$17.1^{+12.8}_{-5.2}$	14.4
	$16.4^{+12.3}_{-5.0}$	13.7
	$16.7^{+12.5}_{-5.1}$	14
J1856	$d = 122$ pc	
	$16.7^{+2.2}_{-1.8}$	14.0
	$17.5^{+2.2}_{-1.8}$	14.8
	$14.9^{+1.9}_{-1.6}$	12.1

for our distances

Age and temperature for cooling models

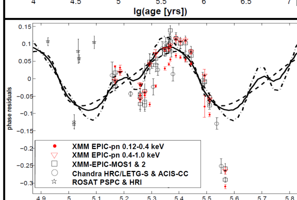
Usually, the age of a NS is estimated by the period and period derivative. The so-called characteristic/spin-down age does not account for gravitational radiation, higher multipole orders of the magnetic field and past accretion events, thus gives only a rough estimate of the true age. 70-80% of all NSs are born in a OB cluster and/or a binary system. After the supernova, the NS will be ejected from its parent association/cluster, and – if a binary-, the companion would be ejected as runaway star. By tracing back the travel paths of the M7 and 3M with known distances and proper motion, using a Monte-Carlo simulation (that takes all errors into account), we can identify the most probable kinematic age τ_{kin} and distance of the supernova from the parent association /cluster (figure on the right).

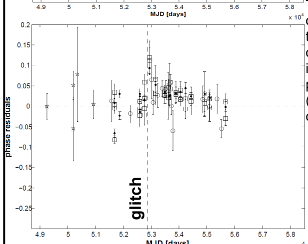




Using the kinematic ages and the temperatures from X-ray spectroscopy, we can compare both quantities with cooling curves (that depend on mass, composition/EoS and cooling process). On the left, we show cooling curves with the characteristic ages (black symbols) and our kinematic ages (red symbols), see also Tetzlaff et al., (2009, 2010, 2011; the cooling curves are taken from Blaschke, 2006 and Gusakov et al., 2005). Note, that our kinematic ages are in better agreement to the cooling curves than the characteristic ages. In the case of RX J1605, the characteristic age is not known, i.e. our kinematic age provides the first age estimation. We will try to determine the kinematic ages of all pulsars younger than 50Myrs by identifying their birthplaces and/or runaway companion in further work.

X-ray timing: free precession and glitches





The X-ray pulsar RX J0720 exhibits long term variations of its spectral and temporal properties, that is unique among all NSs. These variations can be caused by a glitch (van Kerkwijk et al, 2007) or free precession (Haberl et al., 2006, Hohle et al., 2009). If the NS is composed of a superfluid interior, free precession should be damped after 100-1000 cycles (Link, 2003). On the other hand, the precession period and the spin period yield the ellipticity of the NS, that is a cruical input for population syntheses of objects that emit detectable gravitational waves. Based on the observations available at 2009 we created a model of a free precessing NS with different emission geometries, taking all general relativistic effects into account, as well as an updated glitch model (see Hohle et al., 2010 for the glitch model), by fitting the phase residuals. The precession model yield a long term period of 14yrs for the best fit. The phase residuals of the most recent observations (3 Chandra HRC observations in 2010 and one XMM observation in April 2011), are better in agreement with the predictions of the updated glitch solution (left, bottom), than with the model of free precession (left, top).

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