OBSERVATIONS OF COOLING NEUTRON STARS

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Abstract
Observations of cooling neutron stars allow to measure photospheric radii and to constrain the equation of state of nuclear matter at high densities. In this paper we concentrate on neutron stars, which show thermal (photospheric) X-ray emission and have measured distances. After a short summary of the radio pulsars falling into this category we review the observational data of the 7 radio quiet isolated neutron stars discovered by ROSAT which have been studied in detail by Chandra, XMM-Newton and optical observations. Their spectra show blackbody temperatures between 0.5 and 1 million Kelvin and an optical excess of a factor of 5-10 over the extrapolation of the X-ray spectrum. Four of these sources show periodicities between 3.45 and 11.37 sec indicating slow rotation. The pulsed fractions are small, between 6 and 18 %. The magnetic fields derived from spin down and/or possible proton cyclotron lines are of the order $10^{13} - 10^{14}$ G. We then discuss RX J1856.5–3754 in detail and suggest that the remarkable absence of any line features in its X-ray spectrum is due to effects of strong magnetic fields ($\sim 10^{13}$ G). Assuming blackbody emission to fit the optical and X-ray spectrum we derive a conservative lower limit of the “apparent” neutron star radius of $16.5 \times (d/117 \text{ pc})$ km. This corresponds to the radius for the “true” radius of 14 km for a 1.4 M⊙ neutron star, indicating a stiff equation of state at high densities. A comparison of the result with mass-radius relations shows that in this case a quark star or a neutron star with a quark matter core can be ruled out with high confidence.

Keywords: Neutron Stars, Thermal radiation, Equation of State

Introduction and History
1960’s and 1970’s: The rocket experiments and the early satellites like Uhuru and Ariel-5 were not sensitive enough to detect the weak and soft thermal emission of neutron stars. A speculation by Chiu (1964) that the X-rays from the Crab nebula were due to a hot neutron star with kT $\sim$4 keV was soon disproved by the famous NRL lunar occultation experiment which found only an extended source (Bowyer et al. 1964).
1980’s: The Einstein observatory gave the first sensitive upper limit for the temperature of the Crab pulsar, $kT < 0.2\text{ keV} \ (3\sigma)$ (Harnden & Seward, 1984). It is remarkable the most recent upper limit obtained with Chandra is not much lower, namely $<0.17\text{ keV} \ (3\sigma)$ (Weisskopf 2004). The obstacles are the huge magnetospheric emission and the large interstellar absorption, apart from problems with the Chandra-HRC timing. As far as other pulsars are concerned Einstein and EXOSAT yielded only upper limits for their thermal emission as well.

1990’s: A breakthrough came with ROSAT due to the excellent soft response of its PSPC. Thermal emission from a number of pulsars could be clearly identified while ASCA measured the “hard power law tails” which are of magnetospheric origin. Among these sources are PSR 1055–52, PSR 0656+14 and the newly discovered Geminga which have been called the “three musceteers”. Perhaps even more important was the ROSAT discovery of a new class of thermally emitting neutron stars, which show no radio emission and no hard spectral tails, viz. no indication for magnetospheric emission. These objects called “isolated neutron stars” are the main subject of this paper (Sometimes they have been called X-ray dim isolated neutron stars – XDINS –, but this is misleading because they are quite bright in X-rays, but dim in optical light).

2000’s: Recently radio pulsars and isolated neutron stars have been studied extensively with the new powerful X-ray observatories Chandra and XMM-Newton which, taken together, provide a very substantial increase in collecting power, angular resolution, spectral bandwidth and spectral resolution compared with ROSAT and other previous missions.

One of the fundamental problems of neutron star physics is to determine the equation of state at supra-nuclear densities. In order to get a handle on that one must constrain the mass-radius relation and this can be done in principle by various methods which all have their specific problems:

- Measurement of the gravitational redshift of spectral features. Problems: Identification of the feature, large spectral shifts in superstrong magnetic fields.

- Measurement of the surface gravity by analysing the radiative transfer in the neutron star photosphere. Problem: The method is not very sensitive and accurate.

- Measurement of characteristic frequencies (QPO) in accreting sources (see contributions of M. van der Klis, and F. Lamb in this volume).

- Measurement of the photospheric radius. Main problem: Requires knowledge of the source distance.
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We will discuss this method in more detail in this paper which will be organized as follows: In section 1 we will give a short summary of the X-ray emitting radio pulsars concentrating on those sources which have measured parallaxes. In section 2 we will review the properties of radio quiet isolated neutron stars, and section 3 will be devoted to the brightest of these sources, the enigmatic object RX J1856–3754 for which measurements of the parallax exist.

1. X-ray emitting radio pulsars

Three different X-ray spectral components have been identified in radio pulsars:

- The magnetospheric radiation, which is characterised by beaming and a power law spectrum. This component dominates the emission of very energetic pulsars and decreases rapidly with age.

- Thermal emission from the polar caps, which are heated by the bombardment by high energy radiation/particles from the magnetosphere, or by heat outflow from the core region. This component has been detected in middle age pulsars like PSR 0656+14 and millisecond pulsars (RX J0437–47). Since millisecond pulsars should have a cool core, their polar caps must be heated by magnetospheric bombardment.

- Thermal radiation from the bulk surface, which is heated by core cooling. The alternative possibility of heating by low level accretion has not been positively identified yet.

What has just been said is reflected in the distribution of the ~50 X-ray detected radio pulsars in the P-dP/dt diagram shown in Fig. 1. Evidently, we see just those pulsars in X-rays, which have the largest spin down power (∼dP/dt P^{−3}), or youngest age (∼dP/dt P^{−1}).

The multicomponent spectra of three middle age pulsars depicted in Fig. 2 clearly show the huge thermal peaks above the background of the broad-band nonthermal (magnetospheric) emissions. We note that a similar spectrum has been found in PSR 1055–52, the third of the three musketeers. On the other hand, the rather young pulsar PSR J1811–1926 (64 ms, 24000 yrs) shows only a thermal component but no hard tail, which would indicate magnetospheric emission (Mc Gowan 2003). Obviously, the visibility of the beamed magnetospheric emission depends crucially on the orientation of spin axis and magnetic axis with respect to the line of sight.

Of special interest is the small subsample of pulsars for which distances are known from optical or radio parallaxes:

For PSR 0656+14 the distance has been determined using the VLBA (Brisken et al. 2003), resulting in d = 288^{+33}_{−27} pc which is significantly lower than the
Fig. 1: \((P, dP/dt)\) distribution of radio pulsars (black dots). X-ray emitting pulsars are indicated by grey filled circles, stars, squares. Triangles: X-ray emitting millisecond pulsars (Becker 2004). Open circles: radio quiet isolated neutron stars (see text).
long used dispersion distance of 850pc. Using magnetized hydrogen atmo-
spheric model fits Brisken et al. (2003) find a radius $R \sim 13-20$ km, while the
analysis of Pavlov et al. (2002) yields $R \sim 30$ km (scaled to the distance of
288 pc). Here and in the following $R$ represents the radius measured by a dis-
tant observer.

For Geminga the parallax has been determined from HST observations which
give $d = 157^{+59}_{-34}$ pc and a blackbody radius $R_{bb} \sim 9$ km (Caraveo et al. 1996). According to Zavlin & Pavlov (2002) the hydrogen/helium photospheric model fits in general yield radii which are larger by a factor 2-7 compared with black-
body fits, while those for magnetized H/He atmospheres are between nonmag-
netic and blackbody radii. In the absence of a more detailed analysis of the soft
Geminga spectrum we conclude that the radius is probably substantially larger
than 10 km.

The Vela pulsar has a VLB distance of 290 pc (Dodson et al. 2003) which
for a magnetized hydrogen atmosphere model leads to a radius $R = 17-20$ km
(Pavlov et al. 2002).

In summary, the observations point to radii measured at infinity of 14-20 km.

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**Fig. 2: Multiwavelength spectrum of radio pulsars with known distances.**

(a) The solid line shows the NS hydrogen atmosphere plus PL fit to the observed
Chandra spectrum. The dotted line is the unabsorbed model flux. The dash-
dot lines show the extrapolated optical and EUV absorbed spectra (Zavlin & Pavlov 2003).

(b) Three component (TS+TH+PL) model for PSR B0656+14. The absorbed and unabsorbed
spectra are shown with solid and dashed curves, respectively. The crosses
show the IR-optical-UV fluxes (Zavlin & Pavlov 2003).

(c) Geminga spectrum with extrapolations of the total X-ray spectrum (long
dashes) and its thermal component into the optical domain (Zavlin & Pavlov 2003).
2. Radio Quiet Isolated Neutron Stars

The excellent soft X-ray response of ROSAT pointed and all-sky observations (see Trümper 1983) have led to the discovery of seven radio quiet, thermally emitting neutron stars which have been dubbed “the magnificent seven”. A review of the observations can be found in a recent paper of Haberl 2004. The measured blackbody temperatures are between $kT = 44 - 96$ eV, and the optical magnitudes are fainter than $24^m$ (c.f. Table 1). All X-ray spectra show a low interstellar absorption, indicating that the objects are nearby, closer than a few hundred pc. For three of the sources proper motions could be measured which turn out to be very high, implying high space velocities and close distances. None of the sources shows an obvious association with a known supernova remnant, which suggests that they have ages $\geq 10^5$ yrs.

Four of the seven sources show X-ray pulsations with periods of typically 10 sec and pulsed fractions of typically 10% (c.f. Table 1), suggesting that the neutron stars have an inhomogeneous temperature distribution.

| Source name | P (s) | p. fr. (%) | $L_x$ (erg s$^{-1}$) | $kT_{BB}$ (eV) | d (pc) | Opt. mag | pr. mot. (mas/y) |
|-------------|------|-----------|---------------------|--------------|-------|---------|-----------------|
| RX J0420.0-5022$^a$ | 3.45 | 12 | $2.7\times10^{30}$ | 44 | $100^a$ | B>25.5 | - |
| RX J0720.4-3125 | 8.39 | 11 | $2.6\times10^{31}$ | 85 | $100^a$ | B=26.6 | 97 |
| RX J0806.4-4123 | 11.37 | 6 | $5.7\times10^{30}$ | 95 | $100^a$ | B>24 | - |
| 1RXS J130848.6 | 10.31 | 18 | $5.1\times10^{30}$ | 90 | $100^a$ | $m_{50CCD}$ | - |
| +212708 | - | - | $1.1\times10^{31}$ | 92 | $100^a$ | B>27 | 145 |
| RX J1605.3+3249 | - | - | $1.5\times10^{31}$ | 63 | 117 | V=25.7 | 332 |
| RX J1856.5-3754 | - | - | $1.1\times10^{31}$ | 90 | $100^a$ | R>23 | - |
| +065419 | - | - | $1.5\times10^{31}$ | 63 | 117 | V=25.7 | 332 |

$^a$Assumed distance

The slow down rate measured for RX J0720–3125 (henceforth RX J0720) leads to estimates of the magnetic field of $\sim 3 \times 10^{12}$ G and of the age of $10^6$ years. A few of these objects exhibit small but significant changes of the spectra with pulse phase which may be explained by the anisotropic emission of strongly magnetized plasmas. Four of the sources show broad absorption line features which have been attributed to proton cyclotron absorption/scattering in magnetic fields of a few times $10^{13}$ G (Table 2). In RX J0720 long term spectral changes have been found (de Vries et al. 2004), which have been interpreted in terms of neutron star precession.

In summary, these findings strongly suggest that these “magnificent seven” are strongly magnetized ($10^{13}-10^{14}$ G), slowly rotating neutron stars having an inhomogeneous temperature distribution over the stellar surface. Their main
energy source must be heat loss from the hot interior (cooling), since accretion of matter from the interstellar medium is too inefficient due to the high stellar velocities. These sources do not show radio emission, probably because either they are evolved beyond the pulsar death line or because their radio beam is too narrow due to their large light cylinder radius.

3. RX J1856–3754

3.1 General Properties

Among the radio quiet isolated neutron stars RX J1856.5-3754 (henceforth RX J1856) is the brightest and the only one with a known distance. Therefore it is best qualified for detailed studies aiming at a determination of its radius, and in the rest of this paper we concentrate primarily on this object.

RX J1856 was discovered serendipitously in a ROSAT PSPC field by Walter et al. (1996). Using the (HST) Walter & Matthews (1997) identified the X-ray source with a faint blue star (V $\sim$ 26 mag). Its distance and proper motion were determined with the HST by Walter & Lattimer (2002), to be (117 $\pm$ 12) pc and 0.33 arcsec/year, respectively. With the VLT van Kerkwijk & Kulkarni (2001) found a faint nebula surrounding the point source which has a cometary-like geometry with a 25° tail extending along the direction of motion. None of the X-ray observations revealed any variability on time scales up to ten years. The so far best upper limit of 1.3% (2$\sigma$) on periodic variations in the range $10^{-3}$–50 Hz has been established by Burwitz et al. (2003) using a XMM-Newton EPIC-pn observation. Chandra LETG observations with high spectral resolution show a spectrum that can be fit by a Planckian spectrum with a temperature of 63 $\pm$ 3 eV, (c.f. Fig. 3). Despite the excellent photon statistics and the good energy resolution of the LETG this spectrum is devoid of any spectral features. Compared with the optical spectrum which shows a Rayleigh-Jeans slope ($\sim$ $v^2$), the X-ray spectrum is reduced by a factor of $\sim$6. Therefore, the overall spectrum of the source has often been described by a two-temperature
blackbody model (e.g. Pons et al. 2002, Burwitz et al. 2003, Pavlov & Zavlin 2003, Trümper et al. 2004).

A large number of papers have been dealing with the questions concerning the nature of this compact object and the proposed answers include everything from “normal” neutron stars with stiff or soft equations of state over neutron stars having a quarks core to bare (strange) quark stars, P-stars etc (for references c.f. Turolla et al. 2003). Before coming back to this topic we want to summarize some more observational data and their immediate consequences in somewhat more detail.

3.2 The Magnetic Field Strength of RX J1856.5–3754

The impressive lack of any significant spectral features in the LETG spectrum excludes magnetic fields of \((1.3 - 7) \times 10^{11} \, \text{G}\) (electron cyclotron lines) and \((2 - 13) \times 10^{13} \, \text{G}\) (proton cyclotron lines), see Burwitz et al. (2003). This leaves the possibility open of a low magnetic field characteristic for millisecond pulsars or a high magnetic field typical for normal pulsars. Unfortunately, due to the absence of a periodicity the usual estimate of the magnetic field

![Graphs showing photon counts per square centimeter per second per keV for different compositions and observed energies.](image)

Fig. 3: The Chandra LETG X-ray spectrum of RX J1856 fitted with (non-magnetic) photospheric models assuming pure iron and solar composition. The best fit is obtained with a Planck spectrum (Burwitz et al. 2003).
of RX J1856 based on the rotating dipole model is not possible. Using phe-
omenological arguments based on the very small pulsed fraction in X-rays
and on a comparison with other objects van Kerkwijk & Kulkarni (2001)] have
argued that the star has a relatively low magnetic field of a few $10^{11}$ G which
may be marginally consistent with the absence of proton cyclotron lines. But
this is not the only possibility. We estimate the magnetic field using the spin-
down luminosity $dE/dt \sim 4 \times 10^{32}$ erg/s required for powering the cometary-
like emission nebula (Kerkwijk & Kulkarni 2001) and the age of the star ($t \sim
5 \times 10^{5}$ years) inferred from its proper motion and the distance to its likely
birthplace in the Upper Sco OB association (Walter & Lattimer 2002). Apply-
ing the model of magnetic dipole braking we find a period of $\sim 1.8$ sec and
a magnetic field strength of $\sim 1.1 \times 10^{13}$ G. We emphasise that these figures
are very similar to those of the second brightest object of this kind, the pulsat-
ing source RX J0720 whose spectral characteristics are very similar to those
of RXJ1856. While the estimate of $dE/dt$ may be considered as rather reli-
able, the age derived from the birthplace argument is not so certain. However,
an age of $t \sim 5 \times 10^{5}$ years (with an uncertainty of a factor of two) is fully
consistent with what we know empirically about the cooling of neutron stars.
We therefore conclude that the magnetic field of RX J1856 is probably large,
i.e. of the order of $>10^{13}$ G. To confirm this, it is necessary to exclude the
alternative hypothesis of a millisecond pulsar (van Kerkwijk & Kulkarni 2001,
Pavlov & Zavlin 2003). To this end a high time resolution observation with
XMM-Newton has already been scheduled.

3.3 The Featureless X-ray Spectrum of RX J1856.5–3754

The main puzzle of RXJ1856 is the observational fact that its X-ray spec-
trum (Fig. 3) is completely featureless. It has been pointed out by Burwitz
et al. (2001, 2003) that nonmagnetic photospheric spectra assuming a pure
iron composition are incompatible with the measured spectrum because the
predicted Fe-L features are not detected with high significance. Even a solar
composition model with its small abundance of metals leads to unacceptable
spectral fits. Doppler smearing of the spectral lines due to fast rotation does not
wash away completely the strongest spectral features (Braje & Romani 2002,
Pavlov et al. 2002)]. On the other hand hydrogen or helium photospheres can
be excluded, because they would over-predict the optical flux by a very large
factor (Pavlov et al. 1996). Therefore any nonmagnetic photosphere can be
firmly excluded. This argument can be extended to magnetized hydrogen and
helium photospheres (Zavlin & Pavlov 2002).

Iron photospheric models have been calculated by Rajagopal et al. 1997
for $B=10^{12.5}$ and $10^{13}$ G. Unfortunately they suffer from the fact that the ra-
diative properties of iron atoms/ions in super strong magnetic fields are not
known exactly, but only in Hartree-Fock approximation (work of Neuhauser et al. (1986). The resulting spectra contain a lot of lines having spacings of 50-100 eV, which could be easily resolved by the LETG (resolution <1 eV). However, according to Neuhauser et al. (1987) the iron energy levels show a $B^{0.4}$-dependence and therefore a magnetic smearing will take place if the flux is integrated over the whole stellar surface. For a dipolar field, with a factor of two variation of the magnetic field between pole and equator, the spectral features would be broadened by 80 - 300 eV. Thus it is at least plausible, that the combination of a dense level structure of the magnetic atoms with a dispersion of the magnetic field produces a spectrum, which appears as a continuum seen with the LETG. We believe that this is the most promising model for explaining the featureless X-ray spectrum of RX J1856.

Alternatively, the absence of any spectral feature may indicate that the star has no atmosphere but a condensed matter surface (Burwitz et al 2001, Turolla et al. 2003). Such a surface is expected to be reflective in the X-ray domain (Trümper & Lenzen 1978), Brinkmann 1980) which could also help to explain the low X-ray/optical flux ratio (see section 3.4). Condensation of surface matter requires low temperatures and strong magnetic fields. To condense hydrogen at a temperature of $kT = 63$ eV a magnetic field of $5 \times 10^{13}$ G is required (Lai 2001). For iron it is not clear i whether a condensate can exist at all. According to Lai (2001) the cohesive energy of iron is uncertain, but condensation may possibly occur at $3 \times 10^{14}$ G (for $kT = 63$ eV) while Neuhauser et al. (1987) conclude that iron cannot condensate at all. Another problem is that in general the optical properties of a condensed matter surface as a function of photon energy, polarisation and magnetic field angle have only been calculated in the continuum (plasma) approximation while the effects of atomic and solid state physics have been neglected. In summary it is not clear whether a condensed matter surface can exist and - if it would - whether it could provide a solution for the absence of line features.

3.4 The “Optical Excess” and the Absence of Periodic Variations of RX J1856.5-3754

Already the ROSAT and optical data had shown that the optical Rayleigh-Jeans type spectrum of RXJ1856 is about a factor of $\sim 3$ brighter than the extrapolation of the X-ray blackbody towards lower frequencies (e.g. Pons et al. 2002). Using current optical data and the LETG spectrum this factor turns out to be even larger, namely factor 5-7 (Haberl 2004). This optical excess has been explained in terms of an inhomogeneous temperature distribution with a hot pole and a cool equator, which would lead to a periodic flux variation as observed for four of the seven sources. However, for RXJ1856 the XMM-Newton data put an upper limit of 1.3% on the pulsed fraction in the range
50-10^{-3} \text{Hz} \) (Burwitz et al. 2003). There are several possibilities to explain this behaviour:

- The rotational frequency could be larger than 50 Hz, viz. the source would be a millisecond pulsar. We regard this case unlikely in view of the arguments on its magnetic fields discussed above. Anyway it will be checked soon by XMM-Newton EPIC pn observations in the high time resolution mode.

- The extreme alternative is, that the neutron star has spun down within \( \sim 10^6 \) years to very long periods, \( P > 10000 \) sec by the propeller effect. This requires an extremely strong magnetic field (\( \sim 10^{15} \) G) and a relatively low velocity (Mori & Ruderman 2003).

- The simplest explanation is that the rotational axis of the neutron star is closely aligned with the line of sight or with the magnetic axis. This may look unlikely in view of the low pulsed fraction of \(<1.3 \%\), but the average pulsed fraction of the other four sources is only \( \sim 12 \%\). Therefore the possibility of an accidental alignment cannot be neglected.

In this context we note that the tight constraint on the alignment could be somewhat relaxed if the X-ray flux were reduced due to reflection effects because the size of the X-ray emitting spot would be increased.

### 3.5 A Lower Limit to the Radius of the Neutron Star RX J1856.5–3754

Whatever the answers to the open questions discussed in sections 3.2.–3.4. are, one can derive a lower limit for the photospheric radius based on blackbody fits for the overall spectrum and on the source distance, as discussed by Burwitz et al. (2003) and Trümper et al. (2004). Indeed, such a lower limit is expected to be a quite conservative one, keeping in mind that a blackbody is the most efficient radiator. With other words: Any real emitter needs to have a larger surface than a blackbody radiator in order to emit the same luminosity. We stress that the application of this rather general “thermodynamic” argument seems justified in view of the shape of the broadband spectrum, which is characterised by a clear Rayleigh-Jeans law in the optical and a Wien-like behaviour at X-ray energies. For our analysis we use the distance of 117 pc, which has been derived from four HST observations (Walter & Lattimer 2002).

We first consider a simple two-component blackbody model for the optical and X-ray spectrum of RX J1856 (Burwitz et al. 2003) which is shown in Fig. 4a. The blackbody radius and temperature of the X-ray emitting hot spot derived from the Chandra LETG spectrum are \( R_x = 4.4 \) km and \( kT_x = 63 \) eV, respectively. The optical spectrum is interpreted as the sum of the Rayleigh-Jeans
spectra of both the hot and the cool component. This fixes \((R_o)^2 \times T_o + (R_x)^2 \times T_x\). The condition that the optical spectrum of the cool component does not show up as a deviation in the X-ray spectrum limits the corresponding temperature to \(kT_0 < 33\) eV at the 3\(\sigma\) level (Burwitz et al. 2003). Using these figures we find for the radius of the neutron star \(R = (R_o^2 + R_x^2)^{1/2} > 16.5\) km (3\(\sigma\)).

As an alternative we use a model with a continuous temperature distribution (c.f. Fig. 4b) of the form

\[ T = T_h \times \left\{ 1 + \left( \frac{\theta}{\theta_0} \right)^\gamma \right\}^{-1} \]  

(1)

The best fit to the overall spectrum yields a central temperature of the hot spot \(T_h = 82\) eV, an angular size of the hot spot \(\theta_0 = 40^0\) and \(\gamma = 2.1\). In this case the neutron star radius turns out to be 16.8 km (3\(\sigma\)), not much different from that of the simpler model.

These apparent radii \(R\) measured by a distant observer are related to the “true” stellar radius \(R_0\) by

\[\begin{align*}
\text{Fig. 4: Blackbody fits to the optical and X-ray spectra of RX J1856.5-3754 for a two-component model (a) and a model with a continuous temperature distribution (b), see text.}
\end{align*}\]
where \( R_s = 2GM/c^2 \) is the Schwarzschild radius. The corresponding bound in the \( M - R_0 \) diagram is shown in Fig. 4. For a standard neutron star of 1.4 solar masses the true radii are \( R_0 = 14.0 \text{ km} \) (Fig. 4a) and \( R_0 = 14.1 \text{ km} \) (Fig. 4b), respectively, and thus considerably larger than the canonical radius of 10 km. This implies a rather stiff equation of state. We note, that the same conclusion was reached by Braje & Romani (2002) using a two-component model and similar arguments. In order to compare our results with the predictions of theoretical neutron star models in more detail we use the mass-radius diagram given by Pons et al. (2002) This diagram is shown in Fig. 5 to which we have added a curve corresponding to the apparent radius of \( R = 16.5 \text{ km} \).

![Fig. 5: The mass-radius relations for various equations of state for the nuclear matter according to [26]. The thick dashed curve represents the apparent minimum neutron star radius derived from both the two-component and continuous temperature blackbody models and a source distance of 117 pc.](image)

It is evident that the result of our analysis excludes the quark star models discussed by Pons et al (2002) and by Schertler et al. (1998). Also the neutron star models with quark matter cores discussed in the latter paper are rejected. We conclude that for a source distance of 117 pc this neutron star must have a very stiff equation of state. Recent improvements of the RX J1856–3754 parallax, which use additional HST observations at four different epochs (Kaplan 2004) yield an even larger distance of 160 pc. This result considerably sharpens our conclusion. In this context one may speculate that a too large radius...
could imply that this neutron star has an anomalously low mass (<0.4 M\(_\odot\)). But that would raise a lot of questions; in particular it is doubtful whether such a low mass neutron star could be formed.

In summary, the observation of RXJ1856–3754 strongly suggest that the size of a neutron star is rather >14 km instead of the canonical size of 10 km. This result gets support from the observations of the three radio pulsars discussed in section 2. This has consequences for pulsar astrophysics: E.g. the magnetic field strengths estimated from pulsar spin down observations have to be lowered by at least a factor of two since \(B \sim R^{-2}\), and the moment of inertia and therefore the estimate of the pulsar rotational energy of a pulsar increases by a similar factor. However, the most important result of our analysis is that the behaviour of nuclear matter at very high densities is governed by a very stiff equation of state.

4. **Outlook**

We have learned a lot about cooling neutron stars from X-ray and optical observations since 1990, and we can hope to learn a lot more from Astro-E, XEUS and Constellation-X in the future. However, an all-sky survey in the soft X-ray band which is at least ten times more sensitive than ROSAT would be most important, to find more and fainter sources of this type. At the same time, it would be necessary to improve the sensitivity of optical observations with instruments of the 30-100 m class in order to measure the faint optical spectra. Finally, it seems essential to develop further our understanding of atomic and condensed matter physics under the conditions of very strong magnetic fields.

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