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The Zoo of Neutron Stars¶

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Abstract—In these lecture notes, I briefly discuss the present day situation and new discoveries in astrophysics of neutron stars focusing on isolated objects. The latter include soft gamma repeaters, anomalous x-ray pulsars, central compact objects in supernova remnants, the Magnificent Seven, and rotating radio transients. In the last part of the paper, I describe available tests of cooling curves of neutron stars and discuss different additional constraints that can help to confront theoretical calculations of cooling with observational data.

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1. INTRODUCTION

Like the Moscow Zoo, the Zoo of neutron stars (NSs) can be separated into *old* and *new* parts. The *old* part includes classical radio pulsars and accreting NSs in close binary systems. This territory started to be filled with "animals" already in the 1960s, and most of the "beasts" are well known even to the general public. The *new* one is mostly populated by isolated NSs which belong to five main types that have mainly been recognized in the last 10 years or so. These five species are soft gamma repeaters (SGRs), anomalous x-ray pulsars (AXPs), central compact objects in supernova remnants (CCOs in SNRs), the Magnificent Seven (M7), and rotating radio transients (RRATs). Perhaps in the near future more types will be recognized (for example, related to unidentified EGRET sources; in this respect data from the GLAST mission will be of crucial importance). In the following section, I try to give an extremely brief guide to this *new* territory of the Zoo of NSs.

As only few words can be said about each type due to a strict page limit, at first I would like to give a list of reviews on each of the types mentioned below. Of course, I cannot even list all the reviews on the subjects, so the choice is very subjective, but, nonetheless, representative.

As a general introduction to the Zoo of NSs, one can take the short encyclopedic article by Baym and Lamb [1] and references therein. SGRs and AXPs are very well described in [2]. The theory of magnetars has been reviewed many times; one can use, for example, the review by Heyl [3]. A perfect recent review on AXPs can be found in [4]. Observations of SGRs are also reviewed in [5]. To have an impression of what CCOs look like, one can examine the brief paper [6]. A huge set of Chandra results on observations of SNRs (including CCOs) can be found in [7]. An extensive search for compact sources in SNRs was presented in [8]. The Magnificent Seven have attracted much interest in the last few years. Two interesting reviewing papers were published recently by Trümper [9] and Haberl [10]. RRATs appeared in the Zoo very recently, so there are no reviews, yet. One should refer to the original paper [11].

In the last part of this note, I speak about tests of theories of the thermal evolution of NSs. A very good recent review on the cooling can be found in [12].

All subjects touched in this paper have been excellently reviewed during the conference "Isolated Neutron Stars: From the Interior to the Surface" (London, April 2006). Proceedings of the meeting will be published soon in the journal Astrophysics and Space Science, and this volume is going to be the best set of materials on the subject in the near future.[1]

Finally, the Russian-speaking reader can have a look at our review [14], where all subjects mentioned here are discussed in more detail.[2]

In Table 1 I give the list of sources. Mostly, data on SGRs are taken from [2]; on AXPs, from [4]; on CCOs, from [6]; and on the M7, from [10]. However, some additions from other publications are made. In particular, I want to underline the recent determination of the spin period of RX J1856-3754 [13].

2. SOFT GAMMA REPEATERS

The first burst of a SGR was detected long ago on March 5, 1979. The source was recognized as an object with spin period about 8 seconds in the SNR N49 in the Large Magellanic Cloud [15, 16]. Since then, three more sources of this type have been discovered, and a few candidates are known, too.

¶ The text was submitted by the author in English.

[1] Many presentations from this conference are available on the Web: http://www.mssl.ucl.ac.uk/% 7Esz/Conference_ files/index.html

[2] This review is available on the Web at this URL: http:// xray.sai.msu.ru/~ polar/html/kniga.html

Table

Name	P, s	$\dot{P}/10^{-13}$	Comments
SGRs			Giant flares
0526–66	8.0	660	March 5, 1979
1627–41	6.4	–	June 18, 1998 (?)
1806–20	7.5	830–4700	Dec. 27, 2004
1900+14	5.2	610–2000	Aug. 27, 1998
AXPs			Remarks
CXO 010043.1–72	8.0	190	SMC
4U 0142+61	8.7	20	Remnant disc
1E 1048.1–5937	6.4	270	Bursts
CXOU J164710.2–455216	10.6	–	Westerlund 1
1 RXS J170849–40	11.0	190	
XTE J1810–197	5.5	50	Transient, bursts
1E 1841–045	11.8	420	SNR Kes 73
AX J1845–0258	7.0	–	Transient, SNR G29.6+0.1
1E 2259+586	7.0	4.8	Bursts, SNR CTB109
CCOs			SNR
J000256+62465	–		G117.9+0.6
J082157.5–430017	–		Pup A
J085201.4–461753	–		G266.1–1.2
J121000.8–522628	0.424	0.13	G296.5+10.0
J161736.3–510225	6.7 hours		RCW 103
J171328.4–394955	–		G347.3–0.5
J181852.0–150213	–		G15.9+0.2
J185238.6+004020	0.105		Kes 79
J232327.9+584843	–		Cas A
M7			Optical magnitude
RX J0420.0–5022	3.45	<92	$B = 26.6$
RX J0720.4–3125	8.39	0.698	$B = 26.6$
RX J0806.4–4123	11.37	<18	$B > 24$
RBS 1223	10.31	1.120	$m_{50ccd} = 28.6$
RX J1650.3+3249	6.88 (?)	–	$B = 27.2$
RX J1856.5–3754	7.05	–	$B = 25.2$
RBS 1774	9.44	<60	$B > 26$

Spin periods in the range ~5–8 s and associations of some of SGRs with young SNRs undoubtly point towards young NSs. Before December 2004 three main types of burst had been recognized: weak, intermediate, and giant. Weak bursts are most numerous; hundreds of them have been detected. Their typical durations are about 0.1 s, and luminosities are $<10^{41}$ erg s^{-1}. They usually have a single-peak structure and tend to concentrate around periods of activity, during which more rare and energetic bursts appear. Intermediate bursts show a variety of morphologies. Their luminosities are about 10^{41}–10^{43} erg s^{-1}. More energetic events are classified as giant bursts. The historic March 5 burst of SGR 0526-66 is one of them. A similar event was detected from SGR 1900 + 14 on August 27, 1998. Some researchers classify the June 18, 1998, burst of SGR 1627-41 as a giant one [32], but it did not have the typical pulsating "tail," so this classification is usually doubted.

The last giant burst of SGR 1806-20, observed on December 27, 2004, is often marked out, and classified as a *hyper flare*. The reason is simple: its energetics is about 2 orders of magnitude higher than in the case of other giant bursts.

One of the main recent discoveries made in observations of these sources is the detection of quasiperiodic oscillations during giant flares [18, 19]. Results were obtained for bursts of SGR 1900 + 14 and SGR 1806 – 20. Oscillation frequencies are about tens of Hz. Most probably, they reflect torsional vibrations of the neutron star crust.

Another intriguing discovery is related to observations of the GRB 051103 [20]. The authors provide evidence that this short gamma-ray burst does not have a cosmological origin, but rather, is a hyper flare of a SGR in the group of galaxies around M81. If confirmed, it is the first clear observation of a SGR outside the local group of galaxies (see, however, [21, 22]).

Standard interpretation of SGRs is related to *magnetars*—NSs releasing their magnetic energy. The reasons is that neither rotational, nor thermal, nor any other kind of energy stored in a NS can explain the observed phenomena. The same interpretation is applied to AXPs, which are assumed to be at least cousins of SGRs.

3. ANOMALOUS X-RAY PULSARS

AXPs were recognized as a separate class among x-ray pulsars in 1995 [23, 24]. Their periods are clustered in a narrow range between ~ 5 and 12 s, they continuously spin down, their luminosities are stable and somehow smaller than for other x-ray pulsars, and, finally, no binary companions have been found for them. Now nine objects of this type are known. Some of them are situated inside SNRs.

The connection between AXPs and SGRs is supported by the following arguments. The first one is the most obvious: they have similar P and $\dot{P}$ values. Then, astrophysical manifestations of both types can be quite similar. In the quiescent state, SGRs share similar properties with AXPs. For example, SGR 0526-66 has shown no signs of bursts since the early 1980s, and it looks like a typical AXP. On the other hand, AXPs can produce bursts [25], which are very similar to weak bursts of SGRs. Finally, for most AXPs, their thermal or rotational energies are not sufficient to explain the observed activity, as it is in the case of SGRs.

One of the main recent results in the field, in my opinion, is the discovery of a remnant disc around AXP 4U 0142 + 61 [26]. The possibility of the existence of remnant discs formed due to fall-back of matter after a SN explosion has long been discussed. The idea of active discs of this kind was considered as the main alternative to the magnetar scenario (at least in the case of AXPs) [30]. Such discs could contribute to the spin down of NSs, and, probably, to luminosity. However, the discovered disc is most probably a passive one; i.e., it has nothing to do with the present-day activity of the AXP.[3]

[3] See, for example, [4] for the critics of the debris disc models.

Another result that necessarily should be mentioned is the discovery of hard tails in spectra of several AXPs [27, 28, 29]. This was done thanks to observations onboard the INTEGRAL satellite. The good sensitivity of this observatory in the hard x-ray range resulted in detection of emission above 10 keV (up to 150 keV) from AXPs 1RXS J1708 – 4009, 4U 0142 + 61, 1E 1841 – 45, and 1E 2259 + 586. This result poses new questions to the theory of magnetar emission.

Finally, it is important to note that AXPs (and, probably, SGRs and M7) should not be considered absolutely radio-silent any more. Radio emission was detected on VLA from the transient AXP XTE J1810-197 [31]. Earlier, detection of low frequency radio signals from an AXP and from a member of the M7 has been reported by the Pushchino group [32].

4. CENTRAL COMPACT OBJECTS IN SUPERNOVA REMNANTS

CCOs are defined as x-ray sources with thermal-like spectra observed close to centers of nonplerionic SNRs without any counterparts in radio and gamma wavebands. They show blackbody temperatures of about a few hundred eV and have luminosities ~10^{33}–10^{34} erg s^{-1}. About ten such sources are known, including the famous RCW103, Cas A, Pup A, and Kes 79. In different papers one can find slightly different lists of sources depending on the criteria used to select them. Also, the number is continuously increasing. For example, the announcement of the last candidate discovery appeared during the preparation of this manuscript [34].

Some of the sources (Cas A, Vela Junior) have, according to spectral fits, surprisingly small emitting areas. Typical sizes for them are <2 km, well below the size of a normal NS. This puzzle remains unsolved.

Recently, a clear 6.7 h period was confirmed in RCW103 [36]. The origin of the periods is unclear: it can be an orbital or a spin period. In the first case, there are strict limits on the secondary companion: it cannot be a normal star with $M > 0.4M_{\odot}$. The companion can be, for example, another NSs [37]. If the newborn NS that produced the SNR has a remnant disc around it, then the older NS can accrete from that disc when passing close to the companion. Another possibility is that the secondary companion is a very low-mass star inside the magnetosphere of a NS (a system similar to so-called *polars*). However, such a system can hardly be formed without a significant kick velocity, but the proximity of the source to the geometrical center of the SNR points to low velocity <150 km s^{-1}. De Luca et al. [36] favor the idea that the observed period is the spin period of an extreme magnetar with $B > 10^{15}$ G. Even with such a field, a NS cannot spin down to 6.7 h via magneto-dipole (or longitudinal current) losses during the lifetime of the remnant. So, a kind of propeller mechanism should be working. The appearance of such a field is doubtful, in my opinion; as in the case of RCW 103,

it has to be the fossil field not significantly amplified due to some kind of a dynamo mechanism, as there are no traces of huge energy input into the SNR (see [38] for discussion of such a limitation). Anyway, whatever the real nature of the source is, it is very peculiar and puzzling.

Another interesting result is related to the source Puppis A. Winkler and Petre [35] found that this object has one of the largest spatial velocities among all known NSs, ~1500 km s^{-1}. This is the first case when proper motion of a CCO has been measured directly.

5. THE MAGNIFICENT SEVEN

The first source of this type, RX J1856-3754, was discovered 10 years ago [39] in the ROSAT data. Later on, six other similar objects were identified, also in the data obtained with the ROSAT. All seven are recognized to be relatively close-by (less than a few hundred pc), middle-age (about several hundred thousands years) isolated NS emitting soft x-rays due to cooling. The latter is confirmed by the blackbody shapes of their spectra. Typical temperatures are about 50–100 eV. At least five out of the seven show spin periods in the range 3–12 s. Recently, discovery of pulsations has been reported also for RX J1856.5 – 3754 [13] and RX J1650.3 + 3249 (see [10] and references therein). The case of RX J1856-3754 is the most spectacular, as before very recent time only very strict limits on any kind of pulsations had been reported [41]. Some of the seven have very weak optical counterparts. For the brightest one (RX J1856-3754), the trigonometric parallax and proper motion are known [40]. These data provide the possibility to reconstruct the 3D trajectory, and so identify the birth site of the NS.

Population synthesis studies [42] show that the M7 are related to the Gould Belt—a local structure with an age of ~30–50 Myrs formed by massive stars. Reconstruction of trajectories of NSs confirmed this conclusion. In the solar vicinity, these NSs outnumber radio pulsars of the same age. This means that the M7-like objects can be one of the most typical young NSs with a galactic birth rate larger than that of normal radio pulsars.

XMM-Newton observations made it possible to detect wide absorption features in spectra of several among the M7. The origin of these features is not known (see [10] for references and more detailed description of the results presented next). They can be proton (or ion) cyclotron lines in a strong (>10^{13} G) magnetic field or absorption lines due to atomic transitions. For two of the M7 (RBS 1223 and RX J0720.4-3125), spectra are shown to be phase dependent. In the case of RX J0720.4-3125, the x-ray spectrum and pulse profile are changing with time with a possible period of about 7 years, which is attributed to the free precession of the NS. The seven objects seem to be the best laboratory to study NS atmospheres and, probably, internal structure [9].

Probably, the M7 are not absolutely inactive in the radio band. The discovery of a radio signal from 1RXS J214303.7 + 065419 + 06 was recently reported in [43]. Still the result does not have a very high significance and has to be verified.

Unfortunately, up to now only seven objects of this type are known. The last one was identified already in 2001 [33]. However, population synthesis studies predict that up to several dozens of sources in the ROSAT catalogue are waiting for their identification. Our recent calculations ([49] and Popov et al., work in progress) demonstrate that new candidates with count rates 0.1–0.01 ROSAT counts per second should be younger and hotter than the seven known sources and should originate from rich OB associations behind the Gould Belt. If not identified in the ROSAT data, they will be uncovered by the eRosita detector onboard the future satellite SRG.

6. ROTATING RADIO TRANSIENTS

The latest major discovery in the field of isolated NSs was made just a year ago. A new type of sources was discovered—Rotating RAdio Transients (RRATs) [11]. These objects emit very short bursts of radio waves. With a complicated analysis, it became possible to measure periods, and for some sources even period derivatives. Periods are about 0.4–7 s, and $\dot{P}$ about 10^{-13} s s^{-1}, so we can be more or less sure that the objects are NSs. No traces of binarity have been noticed. On the P–$\dot{P}$ diagram, the sources are situated in the region of highly magnetized radio pulsars, close (but not very) to the region where SGRs and AXPs are found. Note that the M7 occupy the same part of the diagram.

Only 11 objects are known up to now. But, as the authors of the discovery estimated, their number and birth rate can be very high, even higher than that of normal radio pulsars. If RRATs do not represent a completely new population of NSs, then the only type that can compare by the birth rate are the M7 [44]. One of the RRATs has been detected in x-rays as a thermal source by Chandra [45]. This makes the possible connection between the M7 and RRATs very plausible.

7. ASTRONOMY MEETS QCD: TESTS OF COOLING CURVES

NSs are one of the most favorite astronomical objects in the physics community for several reasons: strong gravity, strong magnetic fields, huge density inside, etc. The huge density is particularly interesting with respect to the subject of the school (see contributions by D. Blaschke, H. Grigorian, J. Berdermann,

I. Parente, N. Ippolito). NSs are objects where astronomy meets QCD.

Testing the behavior of matter in different regions of the QCD phase diagram is an extremely important, but difficult, task. The region corresponding to high density, but low temperature is not studied by terrestrial laboratory experiments, yet. Observations of cooling NSs give an opportunity to get indirect information about physical processes in this region. The idea is to compare calculated cooling curves with some data obtained from astronomical observations. In this section I discuss different approaches to do this.

The most standard test (I dub it below the T–t test) is the following. One just selects sources with known ages and temperatures and confronts data points with theoretical cooling curves. Naively it is assumed that if all data points can be covered by cooling tracks then the model can be considered to be in correspondence with observations.

The main advantages of this test from the point of view of its use by the community are the following two:

(1) It is clear and direct.

(2) Everybody who calculates the theoretical curves can do the test, as observational data is available in the literature.

The test is widely used and was very well described many times (see, for example, [46] and references therein). Thus, we do not give many details. Let us just specify a few disadvantages, which can be overcome if one uses additional tests and considerations.

(A) Well-determined temperatures and, especially, ages are known for very few objects. So, the availability of statistics is not very great.

(B) Usually both—temperature and age—are known with some uncertainties or depend on a chosen model.

(C) Objects with known temperatures and ages form a very nonuniform sample, as they were discovered by different methods with different instruments. Different selection effects are in the game.

(D) Mostly, objects with known age and temperature are younger than 10^5 years.

(E) There are some additional pieces of data that are not used in the analysis (mass distribution, etc.).

Below I briefly discuss several additional methods that can help to improve the situation with confronting theory and observations.

The first (and the main) additional test is based on the Log N–Log S diagram. This diagram is a useful instrument in astrophysics. Here N represents the number of observed sources with observed fluxes (in some energy range) larger than S. So, this is an integral distribution; i.e., it always grows towards lower fluxes. In [47] we proposed to use the Log N–Log S test as an additional tool to probe theoretical cooling curves. The idea of the test is to compare the observed Log N–Log S distribution with the calculated data in the framework of population synthesis approach [48], and to derive from this comparison if the model fits the data.

Our reasoning in favor of the new test is the following:

(1) Thanks to the observations made onboard the ROSAT x-ray satellite, we have a uniform sample of NSs with detected thermal radiation.

(2) The test does not require the knowledge of ages, temperature, etc. Only fluxes (which are well determined) and numbers are necessary to use this test.

(3) The test is sensitive to older (~1 Myr) sources.

(4) All ingredients of the population synthesis scenario except the cooling curves can be relatively well fixed.

One of the main disadvantages of the test is that one needs to have a computer code to test a set of cooling curves. The way out can be to develop a website where everyone can download cooling curves and obtain the Log N–Log S distribution for selected parameters of the scenario. We hope to make such a resource in future. Another disadvantage is related to precision of the population synthesis model. Not all ingredients are equally well known, and a big piece of astrophysical work has to be done to produce a good model. However, we believe that, for young objects in the solar vicinity, this problem can be solved [49].

Two important additions to these tests are the so-called *brightness constraint* [5] and *mass constraint* [51]. In [50] it was proposed to take into account the fact that, despite many observational efforts, very hot NSs with ages ~10^3–10^4 years have not been discovered. If they exist in the Galaxy, then it is very easy to find them (unless interstellar absorption prevents us from seeing a source, but absorption is not equally important in all directions: so there are relatively wide "windows" to observe a significant part of the Galaxy). If we do not see any very hot NSs, then we have to conclude that at least their fraction is very small. Indeed, we can put limits on models of the most slowly cooling NSs. This means that any model pretending to be realistic should not produce NSs with typical masses with temperatures higher than the observed ones. So, this technique is a useful addition to the standard temperature vs. age test.

This constraint is very sensitive to the properties of the crust of a NS (see [50] for details). Fitting the crust, one can usually find a solution to satisfy the brightness constraint. On the other hand, it is important to remember that the Log N – Log S test is not very sensitive to the crust properties. The usage of only the T–t test plus the brightness constraint approach can lead to a wrong solution as both are not very sensitive to the behavior of the cooling curves for ages larger than a few $\times 10^5$ years, and just fitting the crust can help to find a solution which can be shown to be wrong based on the Log N – Log S test, as properties of the internal parts of a NS are not properly selected. We conclude that anyway the Log N – Log S test should be used, too, as such a com-

plex approach helps to made a more complete testing of cooling curves.

Mass constraint can be done if the mass spectrum of NSs is known. The mass spectrum of NSs is an important ingredient of the population synthesis scenario. Normally, if we consider masses in the range $1M_\odot < M < 2M_\odot$, lighter stars cool more slowly. Our estimates of the mass spectrum [47, 51] show that the fraction of newborn NSs with masses larger than ~$1.5M_\odot$ is very small. This means that more massive objects should not be used to explain observations, especially if we speak about bright or/and typical sources. In particular, close-by young NSs, like Vela, should not be explained as massive stars as it is very improbable that we are so "lucky" to have such a young object (age ~10000 years) so close. As we show in [51], this simple constraint helps to reject some models which can successfully pass T–t or/and Log N–Log S tests.

8. CONCLUSIONS

The main conclusion is that NSs seem to appear in more flavors than it was possible to imagine even after the discovery of radio and x-ray pulsars. The Crab pulsar is no longer the most typical young NS, as the total birth rate of other types of NSs is higher than the birth rate of radio pulsars.

The main unsolved questions are related to the origin of differences between different beasts in the Zoo of young NSs, and to possible links between them.

Observations of cooling NSs can help to better understand physical processes happening in superdense matter inside compact objects. New tests and constraints, hopefully, will help to succeed in selecting the actual equation of state of NSs and figuring out the exact cooling mechanisms working in NSs. For details on these subjects, I refer to other contributions in this volume.

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