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Preface

This will be the 9th gathering on neutron star physics in Saint-Petersburg (after those in 1988, 1992, 1995, 1997, 1999, 2001, 2005, and 2008). The topics include rotation powered pulsars, pulsar emission mechanisms, pulsar wind nebulae, magnetars, isolated neutron stars, central compact objects, accreting X-ray pulsars (including millisecond pulsars), neutron stars in low-mass X-ray binaries, X-ray bursts, equation of state, structure and evolution of neutron stars, mechanisms of supernova explosions. The previous conferences in the series were Russian events with participation of some foreign scientists. This conference is international; the working language is English. It is organized by the Ioffe Institute (Saint-Petersburg, Russia), Sternberg Astronomical Institute (Moscow, Russia), and University of Oulu (Oulu, Finland).

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Contents

A new PWN overlapping the VelaJr SNR

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PSR J0855-4644 is an energetic pulsar ($\dot{E} = 1.1 \times 10^{36}$ erg s^{-1}) with a period of 65 ms discovered recently near the South-East rim of the supernova remnant RX J0852.0–4622 (aka VelaJr) in the Parkes Multibeam Survey. The position of the pulsar coincides with an enhancement in X-rays and TeV gamma-rays, which could represent its pulsar wind nebula (PWN). In a recent XMM-Newton observation we have revealed the X-ray counterpart of the pulsar together with an extended emission thus confirming the PWN suggestion. Interestingly, the core of the PWN ($r < 1$ arcmin) exhibits some knots of X-ray emission separated by 180°, suggesting a jet-like structure. The comparison of the absorption column density derived in X-rays from the pulsar and with ^{12}CO and HI observations is used to derive a distance and to discuss a possible association of the pulsar with the VelaJr SNR.

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One dimensional model of gravitational collapse of the stellar core and associated neutrino luminosity

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We compute the collapse of a $1.4M_{\odot}$ iron stellar core in the frame of 1D model [1–3]. The equation of state takes into account photon black-body radiation, a mixture of Fermi gases of free nucleons and ideal gases of Fe, He nuclei (in equilibrium with respect to nuclear reactions), and an electron-positron gas. The problem involves the Boltzmann kinetic equations for electron neutrinos and electron antineutrinos. Neutrinos take part in weak interactions with free nucleons, nuclei, and electrons. In the present calculations, we employed exact expressions for matrix elements of processes [4, 5] of reactions rates (as was done in Refs. [6], [7] and [8]). We started from nearly equilibrium $P \propto \rho^{1+1/n}$ polytropes with $n = 3$. We followed the evolution till the appearance of a neutron star in its final state. The solution gives neutrino luminosities which exhibit narrow peaks with characteristic widths of 10 ms and the maximum luminosity 10^{54} ergs^{-1} due to the shock wave arising during the collapse. Some part of neutrino radiation is absorbed by the stellar envelope but the absorbed energy $\sim 10^{50}$ is about one order of magnitude smaller than that that required for supernova event. It is likely that to achieve the required energy deposition we need to perform 3D calculations [9, 10].

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Rotational mechanism of supernova explosion and gravitational radiation during rotating stellar core collapse

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It is known that a type II supernova (SN) explosion is accompanied by gravitational collapse of a central core of a massive star after the end of its thermonuclear evolution. The kinetic energy of SN is well known from optical observations. The physics of collapse process is also elaborated [1], but the explosion mechanism has not been fully understood in last 40 years. To explain observations one should perform multidimensional hydrodynamical or magnetohydrodynamical simulations with neutrino transport [2–6].

Registration of neutrino signal from SN1987A stimulated the development of the so-called rotational mechanism of SN explosion [7] connected with fragmentation of the collapsing core into two pieces, with subsequent coalescence of two neutron stars after loosing their angular momentum [8–11]. It is very difficult to check this scenario in direct calculations. Therefore, it is important to separate the problem of stability and fragmentation of rotating core and the problem of coalescence in the frame of 3D hydrodynamic code [12] taking into account the reaction of gravitation radiation. Such 3D calculations give information on emission of gravitational waves that is important for planning future gravitational experiments.

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Neutron stars in RMF theory with and without scalar-isovector δ-meson field

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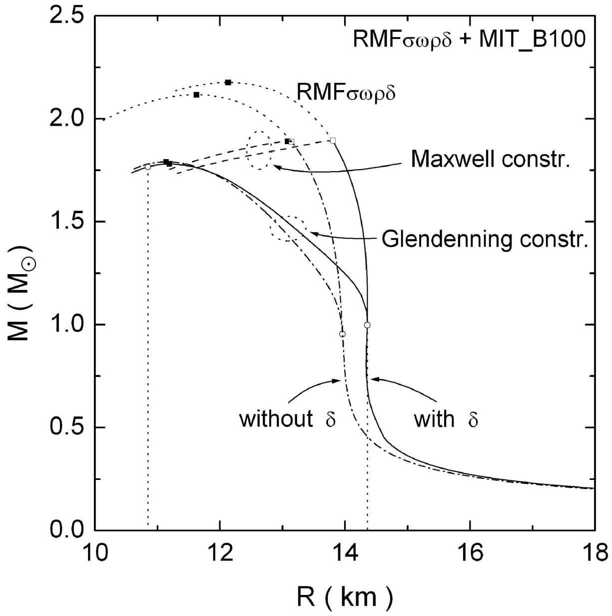

Figure 1: The $M(R)$ dependence of neutron stars with and without δ meson field for the bag constant $B = 100$ MeV/fm^3 (from Ref. [2]).

We have studied the deconfinement phase transition of neutron star matter, when the nuclear matter is described in the relativistic mean field (RMF) theory with δ-meson effective field. We show that the inclusion of scalar-isovector δ-meson field terms leads to the stiff equation of state (EOS) for nuclear matter [1]. In a nucleonic star both the gravitational mass and corresponding radius of the maximum mass stable configuration increases with the inclusion of the δ field. The presence of scalar-isovector δ-meson field alters the threshold characteristics of the mixed phase. For $B = 60$ MeV/fm^3, the lower threshold parameters, n_N, ε_N, P_N, are increased, meanwhile the upper ones, n_Q, ε_Q, P_Q, are slowly decreased. For $B = 100$ MeV/fm^3 this behavior changes to opposite. The range of mass values for stars, containing the mixed phase, is $[0.085M_\odot; 1.853M_\odot]$ for $B = 60$ MeV/fm^3, and $[0.997M_\odot; 1.780M_\odot]$ for $B = 100$ MeV/fm^3. In case of the bag constant $B = 100$MeV/fm^3, the pressure upper threshold for mixed phase is larger, than the pressure, corresponding to the maximum mass configuration (see Fig. 1). This means that in this case the stable compact star can possess a mixed phase core, but the density range does not allow it to possess a pure strange quark matter core. In case of Maxwellian type phase transition, the mass range for stable stars with quark core is $[0.216M_\odot; 1.828M_\odot]$ for $B = 60$ MeV/fm^3.

Stars with δ-meson field have larger radius than stars of the same gravitational mass without the δ-meson field.

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Shear modulus of neutron star crust

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Shear modulus of solid neutron star crust is calculated by thermodynamic perturbation theory taking into account ion motion. At given density the crust is modelled as a body-centered cubic Coulomb crystal of fully ionized atomic nuclei of one type with the uniform charge-compensating electron background. Classic and quantum regimes of ion motion are considered. The calculations in the classic temperature range agree well with previous Monte Carlo simulations. At these temperatures the shear modulus is given by the sum of a positive contribution due to the static lattice and a negative $\propto T$ contribution due to the ion motion. The quantum calculations are performed for the first time. The main result is that at low temperatures the contribution to the shear modulus due to the ion motion saturates at a constant value, associated with zero-point ion vibrations. Such behavior is qualitatively similar to the zero-point ion motion contribution to the crystal energy. The quantum effects may be important for lighter elements at higher densities, where the ion plasma temperature is not entirely negligible compared to the typical Coulomb ion interaction energy. The results of numerical calculations are approximated by convenient fitting formulae. They should be used for precise neutron star oscillation modelling, a rapidly developing branch of stellar seismology.

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Theory of magnetar activity

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Persistent magnetar activity is generated by motions of the neutron-star crust that twist the magnetosphere. Mechanism of the crustal motions will be discussed. The twisted magnetosphere has free energy that can be dissipated, and it tends to untwist over time. The electrodynamics of dissipative untwisting is quite peculiar; it will be illustrated using the simple model of a twisted dipole. The dissipation is associated with electron-positron discharge that fills the magnetosphere with relativistic plasma and creates an extended corona around the magnetar. Plasma circulation in the corona is controlled by the pressure/drag of radiation flowing from the hot neutron star. The corona itself generates nonthermal radiation. Its expected spectrum will be discussed and compared with observations.

Physical and Observed Parameters of Type II-Plateau Supernova

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We present a study of observational and physical properties for a large dataset of highly precise, well-sampled BVI light curves and spectra of type-II plateau supernovae. For this purpose, we calculate (1) a set of parameters that characterize the bolometric light curves, and (2) a grid of hydrodynamical models for a range of progenitor masses, radii, explosion energies, nickel masses, and mixing using a one-dimensional, Lagrangian hydrodynamic code with flux-limited radiation diffusion recently developed by us. We perform a comparison between models and data in a consistent way, and we study correlations between different observed and physical parameters.

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On the mean profiles of radio pulsars

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We study the influence of the propagation effects on the mean profiles of radio pulsars using the method of the wave propagation in inhomogeneous media described in [1]. This approach allowed us to include into consideration simultaneously not only the transition from geometrical optics to vacuum propagation but the cyclotron absorption and the wave refraction as well [2]. It was confirmed that for ordinary pulsars (period $P \sim 1$ s, magnetic field $B_0 \sim 10^{12}$ G) and typical plasma generation (multiplicity parameter $\lambda = n/n_{\rm GJ} \sim 10^3$) the polarization is formed inside the light cylinder at the distance $r_{\rm esc} \sim 1000R$ from the neutron star, the circular polarization being 5–20 % which is just observed. Moreover, the one-to-one correspondence between the signs of circular polarization and position angle (PA) derivative along the profile for both ordinary (O-mode) and extraordinary (X-mode) waves was found. For the X-mode the theory predicts the *same* signs of the circular polarization V and the derivative dp.a./dϕ. For the O-mode the theory predicts the *opposite* signs of the circular polarization V and the derivative dp.a./dϕ. That allowed us in many cases to determine the mode which mainly forms the mean profile of radio emission.

In our work, in addition to effects considered in [2], the arbitrary non-dipole magnetic field configuration, the drift motion of plasma particles, and their realistic energy distribution function are taken into account. It gives us the first opportunity to provide the quantitative comparison of the theoretical predictions with observational data. Using numerical integration we can now model the mean profiles of radio pulsars and, hence, evaluate the physical parameters of the plasma flowing in the pulsar magnetosphere. In particular, it is shown that the standard S-shape form of the PA swing can be realized for small enough multiplicity λ and large enough bulk Lorentz factor γ only. It is also shown that the value of PA maximum derivative, that is often used for determination of the angle between magnetic dipole and rotation axis, significantly depends on the plasma parameters (and differs from the value predicted by rotation vector model). Hence it cannot be used without further refinement of magnetospheric plasma model.

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Monotonous and thousands-of-years cyclic components of isolated radio pulsars spindown

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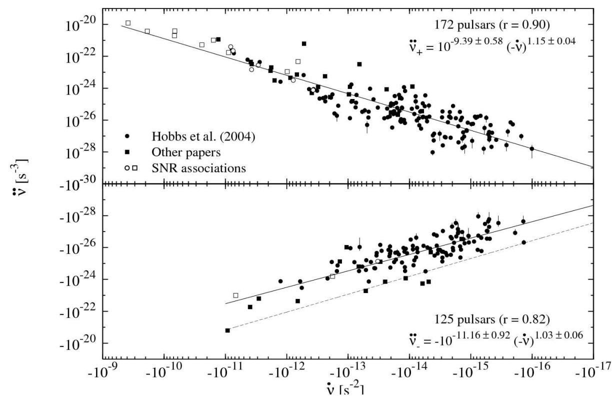

Figure 1: A view of $\ddot{\nu} - \dot{\nu}$ diagram for 297 "ordinary" isolated pulsars. Dashed line is an estimated $\ddot{\nu}$ variation amplitude.

The measurements of pulsar frequency second derivatives have shown that they are from 10^2 to 10^6 times larger than those predicted by canonical magnetodipolar pulsar braking [1]. Moreover, the second derivatives as well as observed braking indices are even negative for about half of the pulsars.

In our work, we revise the problem of anomalous values of pulsars' braking indices. We re-analyze the distribution of 297 ordinary isolated radio pulsars on $\ddot{\nu} - \dot{\nu}$, $\ddot{\nu} - \nu$ and $n_{obs} - \tau_{ch}$ diagrams assuming their spin-down to be a superposition of a "true" monotonous and a symmetric oscillatory terms. As a consequence of the detected strong correlations between these characteristics, we favor for the existence of cyclic variations of pulsar spindown rate on timescales of several thousands of years along with its monotonous evolutionary decrease.

We use the maximum likelihood technique to estimate an evolutionary braking index n and relative amplitude A of $\dot{\nu}$ cyclic variations, assuming A to be constant during pulsar lifetime, but distributed normally over the pulsars subset (with parameters mean $\langle A \rangle$ and standard deviation $\sigma[A]$) and assuming uniformly distributed variational phase. We find $2.5 \leq n \leq 4$ and $0.5 \leq \langle A \rangle \leq 0.9$, with 99% confidence (while most appropriate value of $\sigma[A]$ is close to 0.1). Consequently, real ages of pulsars will be a factor of $0.5 - 3$ of their characteristic ones.

We suggest these oscillations to be connected with the long-term precession of a neutron star around its magnetic axis, probably under the effect of anomalous braking torque.

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Magnetar detectability by the ART-XC telescope aboard Spektr-RG

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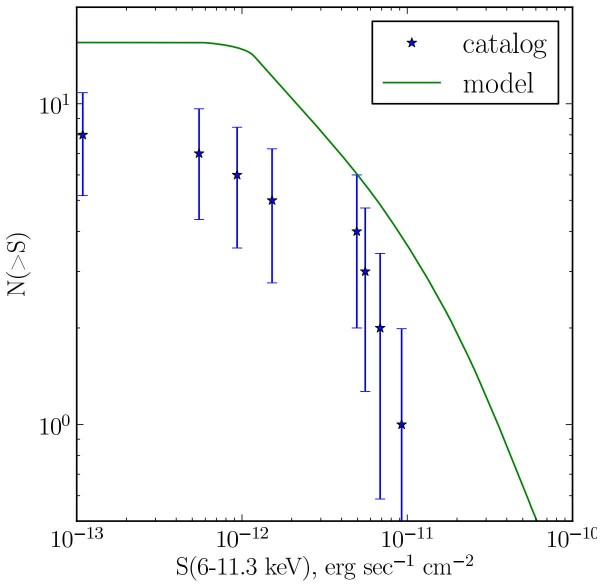

Figure 1: Resulting Log N – Log S

We perform population synthesis calculations to estimate the number of magnetars detectable by ART-XC onboard Spektr-RG satellite. Our calculations show that ART-XC can detect about 4 known and 12 new magnetars. Most of these sources are expected to have a hard power-law tail in their spectra.

Figure 1 shows the predicted Log N – Log S distribution, where S is the flux in the range 6-11.3 keV (where ART-XC has good sensibility in the survey mode). Points correspond to the known sources from [1] with error bars according to the Poissonian distribution, the solid line is the calculated Log N – Log S.

In our model we make the following assumptions: (1) The overall neutron star birth rate is equal to 1/30 yr^{-1}, with the spatial distribution tracing spiral arms of the Galaxy; (2) The initial magnetic field distribution is taken from [2]. It is log-normal with $\langle \log B/[G] \rangle = 13.25$, $\sigma_{\log \mathrm{B/[G]}} = 0.6$. (3) The luminosity versus time dependence is taken from [2]; during the first $\approx 10^4$ yrs the energy released is calculated according to the formula $L(t) = L_0(t) + 0.625\, L_{0\,\mathrm{max}}\, 2^{-2t/14\,\mathrm{kyr}}$, where $L_{0\,\mathrm{max}}$ is the initial luminosity for the highest magnetic field used. (4) Spectra always have Resonant Cyclotron Scattering part [1] with varying parameters (depending on activity state); 20% of time the spectra have also a hard power-law tail up to 200 keV with $\Gamma \approx 1$ containing half of overall luminosity.

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New constraints on thermonuclear bursts from the highest precision X-ray spectra

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X-ray burst spectra have long been used to estimate neutron star masses and radii. These estimates assumed that burst spectra are accurately described by model atmosphere spectra developed over the last three decades. Using RXTE data, we have measured X-ray spectra during several bursts with greater precision than previous measurements and have compared these measurements with the spectra predicted by existing model atmospheres. We find that the spectra predicted by some commonly used model atmospheres are strongly inconsistent with these high-precision measurements. A simple Bose-Einstein spectrum is fully consistent with them and so are some of the recent models of Suleimanov et al. (2011) [1]. I will discuss the prospects for fits to detailed spectral models to constrain both the surface gravity and the redshift, and hence the mass and radius, as well as the systematic errors that must be overcome to achieve this goal.

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Gravitational collapse to third family compact stars

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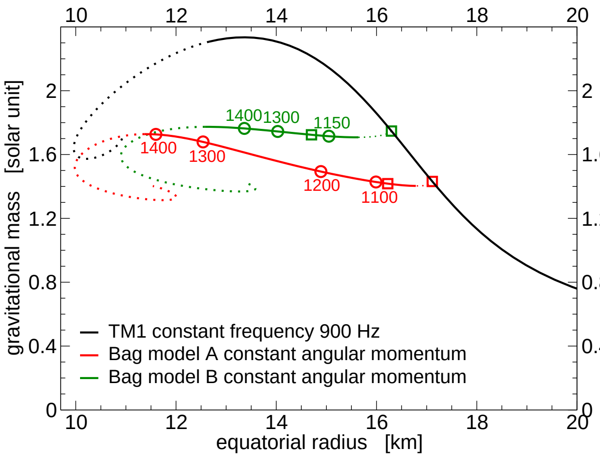

Figure 1: Mass-radius diagram for rotating hybrid stars. Twin star configurations of equal baryon number and angular momentum are denoted by squares. The circles mark stars, for which the value of the angular frequency is given in units of Hz.

The transition from neutron stars to denser stars with a softer equation of state is being discussed since the late 1970's. Even before, Gerlach introduced the concept of a "third family of stable equilibria", besides whites dwarfs and neutron stars.

We present a study of hybrid stars, where the deconfined phase is described by the MIT bag model with finite strange quark mass and superconducting gap. For the equation of state of the normal phase the relativistic mean-field model is employed. The dynamical process of quark core formation is studied with a simplified hydrodynamical approach assuming a constant density core. Effects of the second viscosity on the transition process are discussed. The emission of gravitational waves during the transition of rotationally distorted stars are studied using the quadrupole approximation. Corresponding twin stars are selected by demanding equal baryon number and angular momentum. The impact of the parameter choice for the quark matter equation of state on the energy release and dynamics of the collapse is investigated.

Bekenstein's [2] charge-generalization of Misner's and Sharp's approach for the relativistic radial motion of an ideal liquid is presented in a new form, using Eulerian coordinates.

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Theory of X-ray Bursts, Long Bursts, and Superbursts

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An X-ray burst is the observational manifestation of a thermonuclear runaway in the accreted envelope of a neutron star. With recurrence times of hours to days and durations of seconds to minutes, these explosions are easily monitored and can tell us much about the interior thermal state of the neutron star. While a qualitative understanding of the burst as a thin-shell instability remains the basic model for these events, observations over the last decade have revealed a much richer behavior than predicted by this simple model. In particular, the much rarer long bursts and superbursts (durations of hours) are associated with the ignition at great depth and may inform us about the thermal state of the neutron star's interior. Moreover, strong bursts can power an expansion of the neutron star photosphere, which provides constraints on the neutron star's mass and radius. In this talk, I shall first review the basic physics of the thin-shell instability, and use this as a framework to discuss models for the long bursts and superbursts. I will discuss some of the theoretical challenges in interpreting these bursts, especially for systems accreting at low rates.

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X-ray Outbursts of Transient Anomalous X-ray Pulsars and Soft Gamma-ray Repeaters

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We have studied the long term X-ray outburst light curves of four transient Anomalous X-ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs), namely XTE J1810-197, SGR 0501+4516, SGR 1627-41 and CXOU J164710.2-455216, and have shown that their outburst light curves can be reproduced with the active fallback disk model that was successfully applied to the outburst light curves of persistent AXPs and SGRs in our earlier work [1, 2]. The sets of model parameters used for these transient sources are the same as or very similar to one another and to those employed in our earlier models of persistent AXPs and SGRs [1–3].

The numerical model solves the diffusion equation for the relaxation of a disk which has been pushed back after a soft gamma-ray burst. There is a characteristic difference between the X-ray outburst light curves of the transient and persistent sources. The X-ray enhancements of transient AXPs and SGRs can be explained if there is a critical temperature that leads to thermal-viscous instability at around 1300 – 1400 K for the fallback disks of all AXPs and SGRs. This instability can also be present in persistens sources, but its effects are not observed until $\sim$ 10 years after the outburst. Therefore inserting this critical temperature in our earlier enhancement models of persistent sources does not change the model light curves. This means that a single active disk model can explain the enhancement phases of both transient and persistent AXPs and SGRs with very similar sets of disk parameters. In this picture, the difference between the transient and persistent AXPs and SGRs could naturally be accounted for by their different accretion regimes and corresponding disk temperature profiles.

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Magneto-elastic oscillations and the damping of crustal shear modes in magnetars

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Alfvén oscillations of strongly magnetized neutron stars coupled to shear modes in the solid crust could possibly explain the quasi-periodic oscillations (QPOs) observed in the giant flares of soft gamma repeaters. I present results of two-dimensional simulations of Alfvén torsional oscillations in magnetar interiors, modeled as relativistic stars with a dipolar magnetic field. We use a general relativistic elasto-magnetohydrodynamics code in the anelastic approximation, which allows for an effective suppression of fluid modes and an accurate description of the Alfvén and shear waves. The numerical simulations show that for magnetic field above $\sim 5 \times 10^{13}$ G the pure crustal oscillations are rapidly damped transferring energy to the Alfvém continuum of the core. This result is relevant for the interpretation of the observed QPOs in giant flares, since for magnetar-strength magnetic fields, no crustal modes are expected to be present.

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Magnetic field estimates for accreting neutron stars in massive binary systems and comparison with magnetic field decay models

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Some modern models of neutron star evolution predict that initially large magnetic fields rapidly decay down to some saturation value $\sim$ few10^{13} G. Lower magnetic fields do not decay significantly [1]. It is difficult to check predictions of the model for initially highly magnetized objects on the time scale of few million years. We propose to use Be/X-ray binaries for this purpose. We use several different methods to estimate magnetic field of neutron stars in these accreting systems employing the data obtained by the RXTE satellite [2]. Only using the most modern approach proposed by [3] we are able to obtain a field distribution compatible with predictions of the theoretical model of field decay: even neutron stars with the longest spin periods then have magnetic fields $<$ few10^{13} G.

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Effect of bulk viscosity on Tkachenko modes in superfluid neutron stars

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Superfluids in the neutron star core respond to rotation by forming an array of quantized vortices. The lattice of such vortices can support elastic shear modes called Tkachenko modes [1–3]. The propagation of these waves would lead to observable periodic variations in the rotational frequency of the star [4]. We study the damping effect of bulk viscosity on the propagation of Tkachenko modes in neutron star superfluids, also taking into account the mutual friction between normal fluid and the superfluid, and the shear viscosity [5] of the normal fluid.

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INTEGRAL observations of long X-ray bursts

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Type I X-ray bursts are thermonuclear explosions in the surface layers of a neutron star. They are generally characterized by an exponential decay phase, which duration ranges typically between a few seconds and a couple of minutes, and are explained by the unstable nuclear burning of a mixture of helium and hydrogen. However, some bursts have occasionally been observed with decay times of a few tens of minutes. Because of their duration and energy release these rare long bursts appear as intermediate between the above-mentioned short X-ray bursts and exceptional superbursts that last several hours and are thought to arise from carbon shell flashes in the layers below the surface of the neutron star.

Thanks to the wide field of view of the JEM-X coded-mask X-ray monitor aboard the INTEGRAL satellite many X-ray sources are simultaneously observed in the 3–35 keV energy range, that makes it possible to monitor several X-ray bursters in one shot and/or the occurrence of rare events. So far, a good number of intermediate long bursts have been detected by INTEGRAL, and the mechanisms up to high energies of these unusual events have been investigated. With this research we aim to inquire the relationship between nuclear ignition processes, burning regimes, and accretion states of the binary system, that lead up to long bursts. In particular, a handful of long bursts have been observed that exhibit dual decay phases with an initial spike similar to a normal short burst; we discuss the possibility for such twofold bursts to be some kind of link between different burning regimes. Depending on the composition of the accreted material, intermediate long bursts may be explained by either the unstable burning of a large pile of mixed hydrogen and helium, or the ignition of a thick pure helium layer. The latter case is particularly expected at very low accretion rates, which seem to be prevalent in ultra-compact binaries; it may also provide an opportunity to study the transition from a hydrogen-rich bursting regime to a pure helium regime.

On February 13, 2011, INTEGRAL observed its first superburst, from the transient source SAX J1747.0–2853 (see ATel 3183). At the time of writing, only very preliminary observation results are available, but analysis results from this spectacular event will also be presented at the conference.

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Electrical conductivity of the neutron star crust at low temperatures

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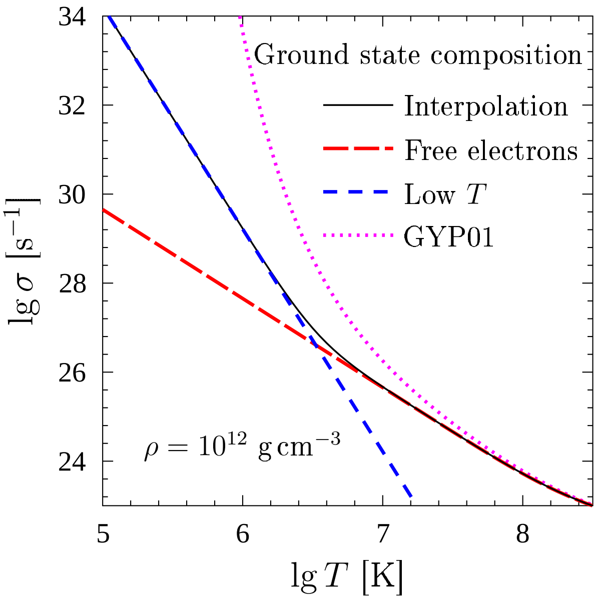

Figure 1: Electrical conductivity σ as a function of temperature T for density $\rho = 10^{12}$ g cm^{-3}.

We calculate electrical conductivity σ of neutron star crust with accurate treatment of the electron state mixing at the vicinity of the Brillouin zone boundaries. The mixing is especially important at low temperatures, where an accurate asymptote of electrical conductivity is derived. We construct an interpolation between new low temperature results and well known high temperature electrical conductivity [1]. This interpolation can be applied at any temperatures.

The results are illustrated on Figure 1, which demonstrates temperature dependence of σ. The ground state composition and density $\rho = 10^{12}$ g cm^{-3} are taken as an example. The short dashed line demonstrates low temperature asymptote of σ. Long dashed line corresponds to the results of [1] based on free electron approximation (neglecting mixing of electron states) that is valid only for sufficiently high temperature. To describe low temperatures, the authors of [1] suggest artificial exponential freezing of the electron-phonon umklapp scattering processes (corresponding σ is shown by dotted line). It leads to an order of magnitude overestimation of σ in the inner crust at $T \lesssim 10^7$ K. A more accurate description of the electrical conductivity at any temperatures is given by our interpolation shown by the solid line. It reproduces low and high T asymptotes and gives smooth interpolation for intermediate temperatures.

This work was partially supported by the Russian Foundation for Basic Research (grant 11-02-00253-a), by the State Program "Leading Scientific Schools of Russian Federation" (grant NSh 3769.2010.2), and by the President grant for young Russian scientists (MK-5857.2010.2).

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Nonradial superfluid modes in oscillating neutron stars

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For the first time nonradial oscillations of superfluid nonrotating stars are studied at finite stellar temperatures. We apply a realistic equation of state and realistic density dependent model of critical temperature of neutron and proton superfluidity. In particular, we discuss three-layer configurations of a star with no neutron superfluidity at the center and in the outer region of the core but with superfluid intermediate region. We show, that oscillation spectra contain a set of modes whose frequencies are very sensitive to temperature variations. Temporal evolution of the pulsation spectrum in the course of neutron star cooling is also analyzed.

This work was partially supported by the Russian Foundation for Basic Research (grant 11-02-00253-a), by the State Program "Leading Scientific Schools of Russian Federation" (grant NSh 3769.2010.2). Work of AIC was supported by the President grant for young Russian scientists (MK-5857.2010.2) and work of MEG by the Dynasty Foundation.

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Theory of the Pulsar Magnetosphere

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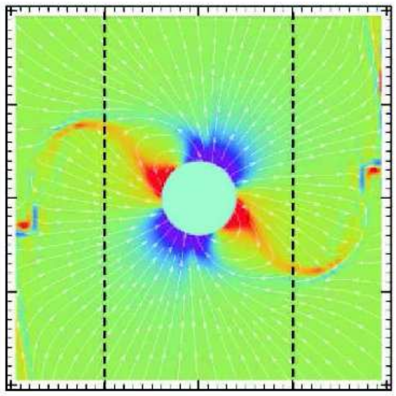

Figure 1: Meridional magnetospheric cross section in a 30° inclined rotator. Arrows: poloidal magnetic field. Colors: electric current density (blue: negative; red: positive). Light cylinder shown with dashed lines (from Ref. [3]).

We will present the main characteristics of the force-free ideal pulsar magnetosphere. We will first analyze the axisymmetric case with particular emphasis on the CKF electric current sheet along the separatrix between open and closed field lines and along the equator [1]. We will then analyze the general three-dimensional case of an inclined rotator [2, 2, 3]. We will present extended numerical simulations that show evidence for regions of focused electromagnetic radiation in the far-field radiation pattern [5]. Finally, we will present recent results on the non-ideal pulsar magnetosphere [6].

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X-ray spectroscopy of X 1822–371: When the accreting neutron star lies hidden

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X 1822–371 is an accreting 0.59 s X-ray pulsar. The system has a 5.57 hr orbital period and the X-ray emission shows a corresponding modulation with dips and eclipses. The source is seen at high inclination angle ($i = 83°$) and the outer accretion disk hides the neutron star from direct observation. Recently two different groups, analysing X-ray and optical data of X1822–371, independently showed that the orbital period derivative is between 1.5×10^{-10} s/s and 2×10^{-10} s/s. This extremely high value is quite surprising, strongly indicating a super-Eddington mass transfer larger than 6 $\times 10^{-8}$ M/yr. This implies that the accretion has to be partially non-conservative and the neutron star should accrete at the Eddington limit [1, 2]. This conclusion means that the intrinsic luminosity of X1822–371 is a factor one hundred larger than what observed from the estimated distance (2.5 kpc), assuming isotropic X-ray emission ($\sim 10^{36}$ erg/s). I will show the first schematic physically self-consistent model to explain this apparent discrepancy, exploiting the most recent Chandra HETGS and XMM-Newton observations of the source. I will focus both on the shape of the continuum emission and the spectroscopic analysis of the emission lines observed in the spectra, and to their variations according to the orbital phase.

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Emission Mechanisms in Magnetar Flares

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The high-amplitude QPOs observed in the tail of flares from soft gamma-ray repeaters are generally linked to physical oscillations of the flaring magnetar. Most work to date has focused on the neutron star's dynamics, and the associated implications of strong oscillations on the star's internal structure. However, an equally important component in understanding these QPOs and the nature of flares comes from understanding how the emission itself is produced, and which correlations are observed between QPO amplitude and rotation phase. In my work I will discuss constraints on the geometry of the flaring magnetar that can be placed from the observed phase profiles and X-ray spectra of flares.

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The Vela and Geminga pulsars in the mid-infrared

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The Vela and Geminga pulsars are rotation powered neutron stars, which have been identified in various spectral domains, from the near-infrared to hard γ-rays. In the near-infrared they exhibit tentative emission excesses, as compared to the optical range [3, 4]. To check whether these features are real, we analysed archival mid-infrared broadband images obtained with the Spitzer Space Telescope in the 3.6–160 μm range and compared them with the data in other spectral domains.

In the 3.6 and 5.8 μm bands we detected at $\sim (4\text{–}5)\sigma$ significance level a point-like object, that is likely to be the counterpart of the Vela pulsar. Its position coincides with the pulsar at $< 0''.4$ 1σ-accuracy level. Combining the measured fluxes with the available multiwavelength spectrum of the pulsar shows a steep flux increase towards the infrared, confirming the reality of the near-infrared excess reported early, and, hence, the reality of the suggested mid-infrared pulsar identification. Geminga is also identified, but only at a marginal 2σ detection level in one 3.6 μm band. This needs a further confirmation by deeper observations, while the estimated flux is also compatible with the near-infrared Geminga excess. The detection of the infrared excess is in contrast to the Crab pulsar, where it is absent, but is similar to the two magnetars, 4U 0142+61 and 1E 2259+586, showing similar features [1, 5].

We discuss X-ray irradiated fall-back discs around the pulsars [2], unresolved pulsar nebula structures, and pulsar magnetospheres as possible origins of the excesses. We note also possible infrared signatures of an extended tail behind Geminga and of the Vela plerion radio lobes.

This work was supported in part by the Ministry of Education and Science of the Russian Federation (contract 11.G34.31.0001).

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New observational results on neutron star crust cooling in transient X-ray binaries

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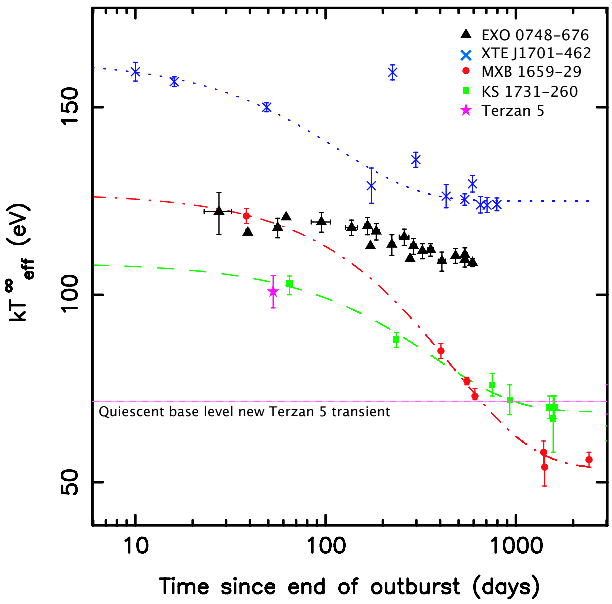

Figure 1: Observed neutron star crust cooling curves for four quasi-persistent neutron star X-ray binaries, including the first data point and pre-outburst quiescent level (horizontal dashed line) of the new transient source in the globular cluster Terzan 5 (this plot is updated from [3]).

When residing in X-ray binaries, neutron stars accrete matter from a companion star. This process induces a series of non-equilibrium nuclear reactions that deposit heat deep in the neutron star crust (e.g., [1]). In transient X-ray binaries, the accretion switches off at some point, which allows the gained heat to be radiated as thermal emission from the neutron star surface (e.g., [2]). By studying the thermal relaxation of the neutron star crust, one can probe important stellar parameters, such as the thermal conductivity of the crust and the dominant cooling mechanism operating in the core, and investigate a variety of processes occurring in the extreme density and pressure environments in the neutron star interior. In the past decade, we monitored the crust cooling curves of four neutron star X-ray binaries that exhibited prolonged accretion episodes of years (e.g., [3] and references therein; see Fig. 1). In addition, we have found the first evidence for crust cooling in an X-ray binary with an outburst of weeks (the recently discovered transient in the globular cluster Terzan 5; [4]). We discuss the new observational results obtained for crust cooling of transiently accreting neutron stars in X-ray binaries.

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Principal physical effects in gyroresonant radiation transfer

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We discuss the main physical processes, which are relevant to gyroresonant radiation transfer in atmospheres of magnetized compact stars. Similar to the wider-studied case of atomic and ion lines, the cyclotron resonance greatly increases the opacity of plasma, leading to formation of radiation-driven winds even at the luminosities much smaller than the Eddington luminosity.

In a strongly magnetized plasma the electrons move essentially in one direction; this sets the transfer of gyroresonant radiation apart from the general case of line radiation transfer, where the scatterers move in all directions. In effect, the cyclotron photons tend to hold resonance with one and the same group of electrons (i.e., the electrons with approximately equal velocities), even though their frequency changes at each scattering due to the Doppler effect. For this reason, the redistribution of photons over frequencies is strongly inhibited, and many authors entirely neglect it. However, the redistribution still proceeds at a very slow pace, owing to finite width of the cyclotron line and – more importantly – owing to relativistic corrections to the resonance condition. The latter allow photons to be in resonance with two separate groups of electrons at the same time, so that few scatterings make photons to change one of their "partner" resonant groups of electrons, causing escape of radiation from the line's core. Here we show that this mechanism plays a principal role in determining the intensity of gyroresonant radiation for neutron star and white dwarf atmospheres in a wide range of parameters.

In addition, the conversion of normal modes due to vacuum polarization drastically increases the radiation pressure force near the photosphere and above it. The cyclotron radiation pressure force is the largest at the top of the atmosphere due to the vacuum polarization effect, which partially converts radiation from the ordinary mode to the extraordinary one, thus enhancing the coupling between photons and electrons.

Both effects should be taken into account for rigorous treatment of the cyclotron-line driven winds.

We also discuss a possibility that interactions of electrons with the cyclotron radiation will cause excursions from local thermodynamic equilibrium (LTE). In the cases where this happens, the self-consistent simulations should include solution of the kinetic equation for electrons. We argue that the net effect of non-LTE corrections is the increase of mass loss rate, which can be sufficiently large to become dynamically important (for example, causing the loss of angular momentum in isolated stars).

Disk-Magnetosphere Interaction in Neutron Stars

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One of the unsolved problems of accretion on a rotating star with a dipole magnetic field is the mechanism that moves plasma from the disk into the funnel flow (Romanova et al. 2002). Balbus & Hawley (1991) showed that differentially rotating accretion disks are dynamically unstable in the presence of a weak magnetic field. This is known as magneto-rotational instability (MRI). We study the efficiency of MRI in moving plasma into the pulsar magnetosphere. We solve the magnetohydrodynamic equations by taking the diamagnetic effects into account. We investigate the instability of the mode with a wave vector perpendicular to the disk. Our preliminary results indicate that the magnetic field and the velocity gradient produced by magnetization current are important in triggering the MRI. We also obtain that the growth rate of the unstable mode is strongly affected by the angle between the magnetic and spin axes.

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Magnetic fields of slowly rotating accreting pulsars

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We present the results of an in depth study of two long-period X-ray pulsars, GX 301−2 and Vela X−1. We show that in both cases the observed long pulse periods and the pulse period evolution, the flux and energy dependence of the pulse profiles, the so-called "off states" reported for both sources, the noise power spectrum of X-ray emission, and in case of Vela X−1 the observed quasi-periodic oscillations, can be naturally explained in a consistent way if the neutron star is strongly magnetized with $B \sim 10^{13} - 10^{14}$ G. We argue that the apparent contradiction of this estimate with the energies of cyclotron lines observed in these sources (which imply an order of magnitude weaker field) can be reconciled if one assumes either that the scattering region is situated away from the surface of the neutron star (in the accretion column or the accretions stream), or that the observed features are due to the improper modeling of the broadband X-ray continuum.

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Pulsar-wind nebulae: Studying particle SED and its evolution with spatially-resolved spectra

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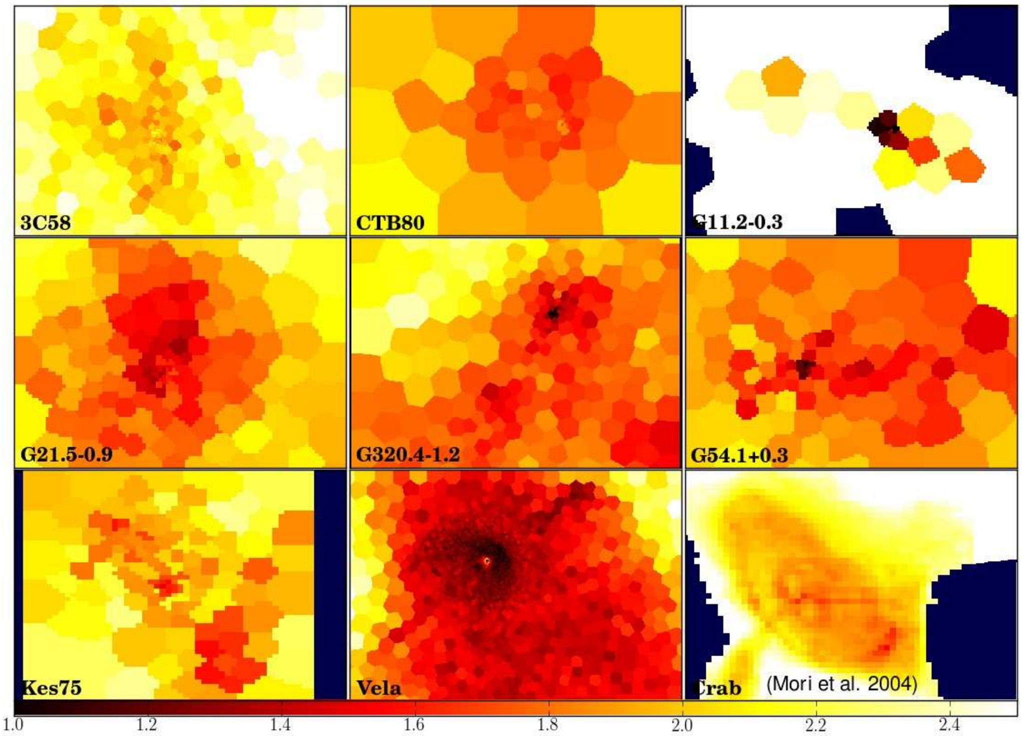

Figure 1: Photon index maps of the PWNe in our sample.

We present adaptively binned spectral maps of eight bright, well-resolved pulsar wind nebulae (PWNe) obtained using all the archival Chandra data available. The maps reveal changes in the spectral index with distance from the pulsar and correlations between the PWN elements and features in the spectral maps. Comparison of spectral indices for PWNe in our sample reveals significant differences. In particular, we find that the spectral indices measured just downstream of the termination shock (reflecting the injected particle spectral energy distribution – SED) vary significantly among PWNe in our sample. We also discuss the implications for particle SED and particle acceleration mechanisms.

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Towards a phase diagram for accreting neutron star crusts: free energy calculations of close packed lattices

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Neutron star crusts are somewhat less exotic than their cores, but may still play an important role in observable astrophysical phenomena, such as pulsar glitches, cooling rates and gravitational wave radiation. Recent nucleosynthesis calculations of accreting material being burned and buried on a neutron star crust indicate the possible presence of many species, ranging from around Z=8 to Z=34. In the outer crust regime where these species are completely pressure ionized and have screened-Coulomb interactions due to the relativistic Fermi electron gas, we expect some close-packed lattices may have a lower free energy than the bcc structure that is usually assumed to exist. Our poster shows the results of ground state and finite temperature free energy calculations for several candidate close-packed lattices. In addition to single-component lattices, these candidates include multi-component lattices found by genetic searches for close-packing in systems of mixed-radius hard spheres.

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Evolution of SGR 0418+5729

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Among the soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs), SGR 0418+5729 is the first source which is known to have a magnetic dipole field less than about 10^{13} G on the surface of the neutron star, deduced from the measured upper limit on the spin-period of the source (Rea et al. 2010). With this dipole field, it is rather unlikely that a neutron star spins down to the observed spin period (~ 9 s) of SGR 0418+5729 by the dipole torques while it is still observable with X-ray luminosities powered by intrinsic cooling of the neutron star. We summarize here how the fallback disk model could produce self consistently the present luminosity, the spin period and the spin-period derivative of SGR 0418+5729 in timescales of several 10^5 years, based on the results of the recent work by Alpar et al. (2011). We also discuss the possibilities of evolutionary links between AXPs, SGRs and XDINs.

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Ultraluminuos SN2009de: an end of evolution of a supermassive star?

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In our report we discuss the result of the photometric and spectroscopic observations of the ultraluminous supernova SN2009de. Observations were performed with SAO RAS 6-meter and Catalina Real Time Survey telescopes as well as with Keck-I 10-meter telescope. The absence of strong hydrogen and helium lines in the spectra and a comparison of our SN2009de spectra with ones of known types indicated that the observed event belongs to supernovae of Type Ic. The identification of the host galaxy emission lines in the spectra allowed us to measure the redshift of the supernova, $z = 0.31$. At the maximum of its light curve the event was as bright as $M_{clear} \simeq -21.8$ (uncorrected for extinction in the host galaxy). Thereby one may refer this object to the class of the most luminous supernovae detected so far. It is interesting that according to its photometric and spectral properties the SN2009de is very similar to the other extremely luminous Type Ic supernova SN2009bi[2, 3]. Proposed models of such luminous explosions require very high masses of the ejected matter, $M_{ej} \sim 40\, M_{\odot}$ and $M_{^{56}Ni} \sim 6\, M_{\odot}$, as well as high kinetic energy $E_{kin} \sim 10^{52}\, erg$ [1]. The most intriguing fact is that all models require also a very massive star ($M_{progenitor} \sim 100 - 230\, M_{\odot}$ at the Main Sequence) of a low metallicity ($Z \leq 0.001\, Z_{\odot}$) as a supernova progenitor. We discuss some of consequences related to this type of supernovae.

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Probing Magnetar Magnetospheres with X-ray Polarization

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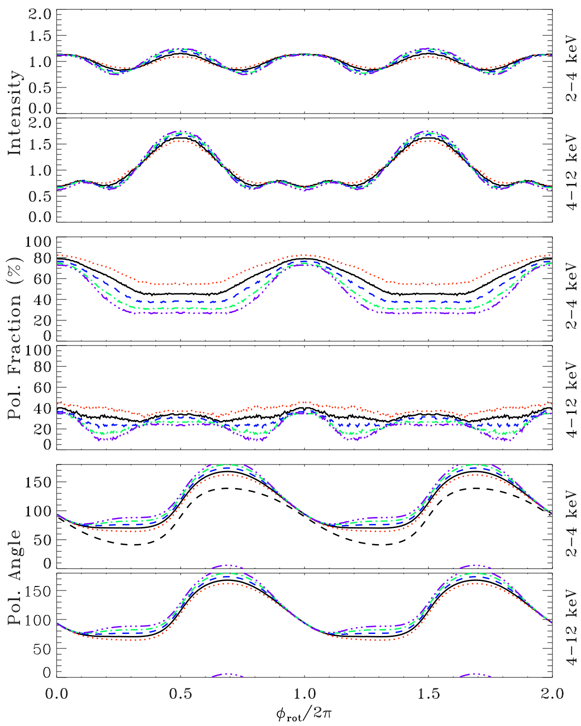

Figure 1: Intensity, pol. fraction, and pol. angle as a function of rotational phase, for a range of magnetospheric twist angles and particle velocities that keep the spectrum nearly constant (from Ref. [2]).

Magnetar candidates are bright X-ray sources. Their quiescent emission in the 1 − 10 keV band is thought to arise from resonant Comptonization of thermal photons in a twisted magnetosphere [1]. Here we report on multidimensional radiative transfer calculations that probe the effects of magnetospheric scattering on the X-ray polarization observables (see [2] for details).

When the pair multiplicity in the magnetosphere is not too large, the dielectric properties are dominated by the magnetized vacuum, and the polarization remains mostly linear until photons escape the magnetosphere.

We find that phase-averaged polarimetry is able to provide a clear signature of the magnetospheric reprocessing of thermal photons and to constrain mechanisms generating the thermal emission. Phase-resolved polarimetry, in addition, can characterize the spatial extent and magnitude of the magnetospheric twist angle at ~ 100 stellar radii (Figure 1), and discern between uni- or bidirectional particle energy distributions, almost independently of every other parameter in the system. We discuss prospects for detectability with GEMS.

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A shallow water analog for asymmetric core-collapse, neutron star kick and spin

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Massive stars end their life with the gravitational collapse of their core and the formation of a neutron star. Their explosion as a supernova depends on the revival of a spherical accretion shock, located in the inner 200 km and stalled during a few hundred milliseconds. Numerical simulations suggest that an asymmetric explosion is induced by a hydrodynamical instability named SASI. Its non radial character is able to influence the kick and the spin of the resulting neutron star. I will review the current status of these discoveries and present the SWASI experiment. This simple shallow water analog of SASI is designed to illustrate the asymmetric nature of core-collapse supernova.

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Modeling the thermal properties of quasi-persistent neutron star X-ray binaries

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Quasi-persistent neutron star X-ray binaries exhibit long active phases, so-called outbursts, lasting from years to decades, during which they accrete matter and have a high X-ray luminosity ($\sim 10^{36-39}$ erg s^{-1}). Then, when accretion significantly decreases, they become quiescent with a lower luminosity ($< 10^{34}$ erg s^{-1}). In the deep crustal heating scenario [1], the matter that is accreted during the outburst undergoes a series of nuclear reactions [2] which heats up the neutron star as the matter sinks deeper into the crust under the weight of the newly accreted material. When the source turns to quiescence, the heat from these crustal sources propagates through the neutron star and is radiated away. As a consequence, the star surface cools.

The modeling of the thermal relaxation and spectral properties of the emission offers a unique opportunity to constraint the properties of neutron stars. The thermal emission in quiescence of four quasi-persistent neutron star X-ray binaries has been observed so far [4], [5], [6], [7]. Previous works [3], [8] show that the cooling of KS 1731−260 and MXB 1659−29 is consistent with a standard neutrino emission, a high thermal conductivity and neutron superfluidity in the crust. During quiescence, a power-law radiation component (of non-thermal origin), was detected in several recent X-ray spectra of EXO 0748−676 and XTE J1701−462 ([6], [7]) pointing out that flares could be associated with residual accretion.

We present models of the cooling of these Soft X-ray Transients under different assumptions concerning residual accretion.

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Observations of Soft Gamma-Ray Repeaters with the Konus experiments

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Soft Gamma-ray Repeaters (SGRs) form a rapidly increasing group of X-ray sources exhibiting sporadic emission of short bursts. Results of observations during recent years indicate that SGRs and Anomalous X-ray Pulsars (AXPs) are basically a single class of highly magnetized isolated neutron stars. Here we report on recent observations of these sources made with two Ioffe Institute gamma-ray burst experiments, Konus-WIND on board the NASA WIND spacecraft and Konus-RF on board the Russian Koronas-FOTON solar observatory. While the well-known repeaters SGR 1806–20 and SGR 1900+14 were mostly quiet, several new sources have manifested themselves in the last few years. Five short bursts from the newly discovered SGR 0501+4516 were detected by Konus-WIND in August of 2008. Properties of the bursts time histories and energy spectra show that the source exhibits itself as a typical soft gamma-ray repeater. However, the bursts peak energy fluxes are comparable to highest of those for known SGRs, so a less distant source is implied, consistent with the determined Galactic anti-center direction. Another new SGR J0418+5729 was discovered as a result of a joint analysis of Fermi-GBM, Konus-RF and Swift-BAT observations of two weak bursts on June 5, 2009. Although the source is also assumed to lie at a nearby distance ($\sim$2 kpc), the small energy fluences of the bursts suggest a presence of the "dim" SGRs population in our Galaxy [1]. In the beginning of 2009 the well-known X-ray pulsar 1E 1547.0–5408 showed a remarkable bursting activity, that reinforces the similarity between AXPs and SGRs. We report on 22 bursts from this source observed with the Konus instruments. The exceptionally bright burst was detected on January, 25, its light curve and luminosity ($L_{peak} \sim 3 \times 10^{43}$ erg s^{-1}) resemble the famous event 980618d from SGR 1627–41 [2].

Finally, we briefly present the second Konus catalog of the SGR's bursts covering the period from 1995 to 2009.

This work was supported in part by the Ministry of Education and Science of the Russian Federation (contract 11.G34.31.0001).

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Modulation of magnetar emission by Alfvén oscillations of the neutron star

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The quasi-periodic oscillations (QPOs) observed in giant outbursts of soft-gamma ray repeaters (SGRs) are commonly interpreted as torsional oscillations of the highly magnetized neutron star (magnetar), which is assumed to be the source of the gamma-ray emission. In this work we extend a study concerned with the analysis of the magneto-elastic oscillations inside the magnetar by allowing the perturbations to extend into the magnetosphere. The latter is assumed to behave as force-free, i.e. we neglect all inertia and pressure terms but allow for magnetospheric currents. In our approach the magnetosphere is evolved quasi stationary as a sequence of force-free equilibrium models, each being completely defined by the magnetic field given at the magnetar surface. This boundary magnetic field is obtained from the simulations of the oscillations of the magnetar interior. The currents maintaining the magnetospheric field configuration are giving rise to a possible mechanism of modulating the emission during the giant flare and hence may explain the observed QPOs in the tail of a giant flare. The mechanism analyzed in this work is that the charge carriers may provide a substantial optical depth due to resonant cyclotron scattering.

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Observations of X-ray bursts

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Thirty years of studying thermonuclear (type-I) bursts from accreting neutron stars have revealed a surprisingly rich spectrum of behavior. A few sources which have been studied intensively offer confirmed examples of two of the three classes of ignition predicted theoretically, and these systems serve as crucial test-cases for numerical models. However, the behavior of the majority of systems cannot be fully reconciled with theoretical predictions, suggesting there is additional physics at work. Additionally, some new classes of bursts have emerged in recent years, including so-called "super" bursts, likely powered by unstable ignition of carbon, and intermediate-duration bursts which likely require a large accreted reservoir of pure helium. In this talk I will attempt to summarize the observational status of thermonuclear bursts, and discuss how well the available nuclear burning and ignition models can reproduce the behavior of various sources. I will also describe an ongoing project, the Multi-Instrument Burst ARchive (MINBAR), which aims to assemble a large sample of bursts observed by recent space missions, to enable comprehensive future studies of rare events and broad-scale behavior.

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Spectral and statistical properties of gyroresonant radiation from compact stars

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We consider transfer of the cyclotron radiation and calculate the radiation pressure force in the hot hydrogen plane-parallel atmosphere of magnetic compact star, taking into account cyclotron scattering, bremmstrauhlung emission and absorption. Also we include into calculation the effect of vacuum polarization and relativistic correction to the cyclotron resonance condition. We provide an accurate treatment of mode conversion effect in the magnetized atmosphere of a compact star employing full evolution equation for the Stokes parameters.

The radiation transfer equation is solved by the modified short characteristics method [1]. We use the condition of no external radiation at the outer boundary. The inner boundary condition means that the radiation intensity tends to its equilibrium value deep in the atmosphere. Also we complement our modeling by Monte-Carlo simulation of the frequency redistribution of gyroresonant photons. We find the mean frequency shift and the mean number of scatterings for photons leaving the atmosphere as function of optical depth at emission, plasma temperature and magnetic field strength. We calculate the probability of the escape of the cyclotron photons from the atmosphere as a function of their optical depth at birth, as well as find the distribution of escaped resonant photons over velocities of electrons at last scattering. These results are necessary for more comprehensive (non-LTE) modelling of compact stars' atmospheres.

Under LTE assumption, the cyclotron wind forms in atmospheres of magnetic white dwarfs for $T \sim 2 - 10$ eV and $B \sim 10^8 - 10^9$ G and in atmospheres of neutron stars for $T \sim 200 - 500$ eV and $B \sim 10^{10} - 10^{11}$ G. The value of a mass loss rate can exceed $10^{-11} M_{\odot}/\mathrm{yr}$. The outflowing plasma can freely move along the magnetic field lines under the influence of radiation driven force. The motion across the field is strongly limited. Thus the part of the ejected plasma forms two polar jets along the open field lines. The rest of the wind is accumulated in the closed part of the magnetosphere and may appear as a dense plasma disk near the magnetic equator [2].

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A Study of Evolutionary Paths of LMXBs

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We discuss formation scenarios of low mass X-ray binaries (LMXBs) and present preliminary results obtained by modern stellar evolution codes (e.g. STARS, MESA [1,2]) for different initial parameters. These results are compared with observations of LMXBs; possible evolutionary stages of LMXBs are outlined. A similar study using the STARS code was presented in [3]. Here we also use the MESA code to analyse possible progenitors of X-ray binaries. We take into consideration mass loss and mass transfer. Binary systems consisting of a 10 $M_\odot$ primary component with a 3.5 $M_\odot$/1 $M_\odot$/0.5 $M_\odot$ secondary component have been modeled for different initial orbital periods. A more detailed study will be presented in [4].

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Similarity of Jupiter and RRATs

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In the present investigation, radial diffusion of equatorially trapped electrons in the magnetospheres of Jupiter and Rotating Radio Transients (RRATs) are examined and compared. It is assumed that electrons lose energy through synchrotron radiation and the wave-particle interaction. The phase space density of the electrons, which go through gradB drift in Jupiter's and RRATs' magnetospheres and thus resonate with the plasma waves, changes and this change predicted by the model seems to be consistent with the Pioneer 10 and Pioneer 11 data for Jupiter's case and a similar result obtained for RRATs. According to our results unusual radio emission of RRATs can be explained by the diffusion mechanism.

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Global equations for the heat transfer in magnetized neutron stars

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Observations on thermal emission from neutron stars can provide not only information on physical properties such as the magnetic field, temperature, and chemical composition of surface but also information on the properties of matter at higher densities, deeper inside the star. There is an anisotropic heat transport in the neutron star's envelope governed by the magnetic field geometry, that produces a non-uniform surface temperature. Observation of periodic changes in thermal (X-ray) emission of rotating neutron stars can provide information on both the magnetic field structure and properties of the matter layers, where the anisotropy of the heat flux is formed.

The anisotropy of the heat flux in a neutron star has been studied by many authors in the one-dimensional approximation, where heat flows along or across a magnetic field. In this paper, the heat equation is derived in the presence of an arbitrary axially symmetric field, with an accurate account of tensor properties of the thermal conductivity. We consider fully ionized relativistic degenerate plasma. The resulting equation will be applied for a study of the heat transfer in dense regions of neutron star crust.

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Population Synthesis of Radio and Gamma-ray Pulsars in the Fermi Era

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We present results of a pulsar population synthesis of both normal and millisecond (MSP) pulsars from the Galactic disk using our earlier developed Monte Carlo code. On the same footing, we use slot gap and outer gap models for gamma-ray emission from normal pulsars to obtain statistics of radio-loud and radio-quiet gamma-ray pulsars. For MSPs, we invoke slot gap and pair starved gamma-ray emission models. We have also improved sky-map intensity phase plots reflecting the geometry and intensity of the emission region. These new phase plots have been calculated to include the offset polar caps of a retarded dipole, which cause a strong azimuthal asymmetry of the particle acceleration around the magnetic axis that dramatically increases parallel component of the electric field and, therefore, increase the gamma-ray luminosity. From a new recent accord of HII and star forming regions in the Galaxy, we develop a surface density model of the birth location of neutron stars. We explore different models of radial birth, supernova kick velocity, initial period, and magnetic field distributions. We present preliminary results including simulated population statistics that are compared with recent detections by Fermi, as well as the simulated diffuse gamma-ray background for normal pulsars.

We express our gratitude for the generous support of the Michigan Space Grant Consortium, of the National Science Foundation (REU and RUI), the NASA Astrophysics Theory and Fundamental Program and the NASA Fermi Guest Investigator Program.

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Resonant Compton Upscattering in High Field Pulsars and Magnetars

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The extremely efficient process of resonant Compton scattering (RCS) in strong magnetic fields is believed to be a leading emission mechanism in high field pulsars and magnetars. We present new analytic developments for resonant Compton scattering, specifically spin-dependent cross sections devised using Sokolov and Ternov electron states. These more technically-correct forms display significant numerical departures from the older Johnson and Lippmann formalism for the cross sections in the resonance, thereby motivating the astrophysical deployment of this updated resonant Compton formulation. Useful approximate analytic forms for the cross section near and at the cyclotron resonance are presented. We highlight the application of these physics calculations in an inner magnetospheric model of the hard X-ray spectral tails in Anomalous X-ray Pulsars (AXPs), recently detected by RXTE and INTEGRAL. Relativistic electrons cool rapidly near the stellar surface, in the presence of intense baths of thermal X-ray photons, where the kinematics dominate and allow thermal photons to easily access the resonance. We present improved RCS electron cooling rates and resulting photon spectra for magnetic fields above the quantum critical value, as functions of the magnetospheric colatitude and altitude. The kinematics provide the framework for an efficient scattering mechanism producing the characteristically flat spectral tails observed in AXPs.

We are also grateful for the generous support of the National Science Foundation (grants AST- 1009731 and PHY/DMR-1004811), and the NASA Astrophysics Theory Program through grants NNX06AI32G, NNX09AQ71G and NNX10AC59A.

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Supergiant Fast X-ray Transients and other wind-fed accretors – testing with the Corbet diagram

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Supergiant wind-fed X-ray binaries and Be-systems occupy different regions in the $P_{\rm spin} - P_{\rm orbit}$ diagram (known as the Corbet diagram). The previous attempts to explain this diagram were not fully satisfactory. We propose a new explanation for the observed dependences which takes into account the fact that the accretting matter in such systems has smaller angular momentum than the Keplerian one. We review properties of the Supergiant Fast X-ray Transients recently discovered with INTEGRAL and note that their location in the Corbet diagram can be a key to understanding of the accretion mechanism responsible for their outbursts.

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Decoupling of superfluid and normal pulsation modes in neutron and hyperon stars

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We show that equations governing pulsations of superfluid neutron and hyperon stars can be splitted into two sets of weakly coupled equations, one describing the superfluid modes and another one – the normal modes [1]. The coupling parameter s of these two sets of equations is small for realistic equations of state. Already an approximation $s = 0$ is sufficient to calculate the pulsation spectrum within the accuracy of a few percents. Our results indicate that emission of gravitational waves from superfluid pulsation modes is suppressed in comparison to that from normal modes. The obtained results explain numerical calculations (see, e.g., [2, 3]) and suggest simple perturbative (in parameter s) scheme which drastically simplify the problem of calculating the pulsation spectrum for superfluid neutron/hyperon stars. In particular, the proposed approach allows us to easily take into account realistic equations of state, dissipation, various composition of matter, temperature effects, baryon superfluidity, density-dependent profiles of baryon critical temperatures, and stellar rotation (see also Ref. [4] where this approach was applied to study non-radial oscillations of superfluid neutron stars).

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Lower Bound on Magnetic Field Strength from SGR's 0526–66, 1806–20, 1900+14 Giant Flares

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Within the framework of the magnetar model, neutrino processes relevant for cooling of an electron-positron plasma producing a SGR giant flare are investigated in details. Modifications of these processes caused by the magnetic field of a magnetar are analyzed. It is shown that the neutrino luminosity of the strongly-magnetized electron-positron plasma is dominated by contributions of the electron-positron annihilation and neutrino synchrotron emission processes. Neutrino energy losses from a region filled by the plasma are calculated for the SGR 0526–66, SGR 1806–20, and SGR 1900+14 giant flares at the stage of pulsating tails. The amount of plasma energy observed in electromagnetic emission from a SGR giant flare can be radiated only in the presence of a strong magnetic field, which suppresses neutrino plasma energy losses. A lower bound on the magnetar magnetic field strength is derived. It is shown that in a wide range of magnetar model parameters, this bound is larger than an upper limit resulted from estimates of the magneto-dipole losses of magnetars analyzed. Therefore, an explanation of observed energy produced in the SGR giant flare at the stage of the pulsating tail is challenged within the framework of the magnetar model.

This work was performed in the framework of realization of the Federal Target Program "Scientific and Pedagogic Personnel of the Innovation Russia" for 2009–2013 (State contract no. P2323); it was supported in part by the Ministry of Education and Science of the Russian Federation under the Program "Development of the Scientific Potential of the Higher Education" (project no. 2.1.1/13011), and by the Russian Foundation for Basic Research (project no. 11-02-00394-a).

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EOS of neutron star cores: Progress, problems, and puzzles

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Recent progress referring to the Equation of State (EOS) of neutron star cores will be reviewed. Precise measurement of the mass of PSR J1614–2230, $1.97 \pm 0.04\ M_{\odot}$ [1] puts stringent constraint on the EOS models. This constraint is particularly challenging for models involving hyperons. It severely limits the possibility of phase transitions in neutron star cores. If massive neutron stars contain quark cores, the quark plasma within them should be strongly correlated. Problems and puzzles that are appearing in the quest for the EOS of neutron star cores will be briefly mentioned.

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Stability Valley of Strange Dwarfs: When Can They Explode?

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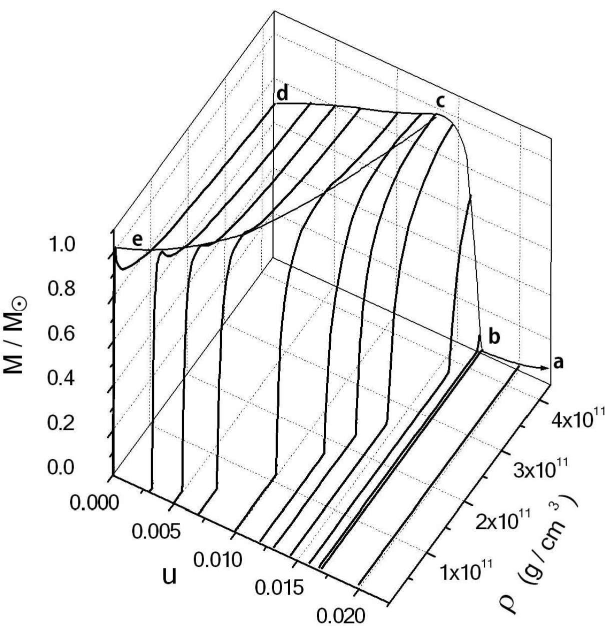

Figure 1: Mass of equilibrium strange dwarfs $M(u, \rho_{tr})$. The region bounded by the curve *ecba* is the valley of stability of these configurations.

Depending on the total number of baryons N_{core} (expressed in solar mass, $u = M(^{56}Fe)N_{core}/56M_{\odot}$) in the quark core and on the energy density of the nuclear-electron crust near the quark core, ρ_{tr}, the range of stability (stability valley Fig. 1) has been determined for strange dwarfs, i.e., superdense configurations having a small quark core and an extensive crust where the density may be two orders of magnitude higher than the density of usual white dwarfs. It is shown [1] that the conclusion on the existence of stable strange dwarfs with the density $\rho_{tr} = \rho_{drip} = 4.3 \times 10^{11}$ g/cm^3 [2] (the density of formation of free neutrons in the cold nuclear-electron plasma) is wrong. Although such configurations have a positive squared frequency of radial pulsations in the fundamental mode ($\omega_0^2 > 0$), they are on the edge of instability towards the transition into the state of strange stars with the same total number of baryons and with the radius on the order of that of neutron stars [1]. These transitions will be accompanied by energy release of the order of that in supernova explosion.

A comparison of masses and radii of strange dwarfs and observed white dwarfs is made. The parameters of white dwarfs are partly refined using the results of program "HIPPARCOS". Among the observed white dwarfs, most possible candidates for strange dwarfs are identified.

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Gamma-Ray Pulsars in the Fermi Era

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The Fermi Gamma-Ray Space Telescope has revolutionized the study of pulsar physics with the detection of over 80 gamma-ray pulsars. Several new populations have been discovered, including 24 radio quiet pulsars found through gamma-ray pulsations alone and about 20 millisecond gamma-ray pulsars. The gamma-ray pulsations from millisecond pulsars were discovered by both folding at periods of known radio millisecond pulsars or by detecting them as gamma-ray sources that are followed up by radio pulsar searches. The second method has resulted in a phenomenally successful synergy, with 35 new radio MSPs (to date) having been discovered at Fermi unidentified source locations and the gamma-ray pulsations having then been detected in a number of these using the radio timing solutions. The higher sensitivity and larger energy range of the Fermi Large Area Telescope has produced detailed energy-dependent light curves and phase-resolved spectroscopy on brighter pulsars, that have ruled out polar cap models as the major source of the emission in favor of outer magnetosphere accelerators. The large number of gamma-ray pulsars now allows for the first time meaningful population and sub-population studies that are revealing surprising properties of these fascinating sources.

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Observations of Central Compact Objects

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I will review X-ray observations of Central Compact Objects (CCOs), which appear to be isolated neutron stars in supernova remnants that are not radio pulsars. Ten CCOs have been identified so far, with a range of X-ray properties [3, 8]. Three show X-ray pulsations [4, 6, 14], and limits on their period derivatives indicate that the magnetic fields of all three are $< 3 \times 10^{11}$ G [5, 7, 8] They have thus been suggested as a class of "anti-magnetars" born with slow spin and low magnetic field. Two CCOs show clear spectral features; 1E1207.4–5209 shows 3 or 4 absorption lines interpreted as electron cyclotron absorption lines [1, 12], while a (possible emission?) feature has been identified around 0.8 keV in the CCO in Puppis A [6]. Inferred sizes of most CCOs suggest hot spots, but the lack of pulsations from several has posed a puzzle, which may be solved by the suggestion of a carbon atmosphere on the Cas A CCO [10]. Such an atmosphere might be produced by diffusive nuclear burning of hydrogen and helium on the young neutron star [2]. The Cas A CCO shows evidence of cooling by 4% over 10 years [9], interpreted as neutrino emission from the transition of neutrons to a superfluid within the core [11, 13].

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Recent Progress in Observations of Magnetars

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The magnetar model has been proposed by Thompson and Duncan first to explain the enigmatic behavior of Soft Gamma-ray Repeaters (SGRs) and later also that of Anomalous X-ray Pulsars (AXPs). Many of the (out)bursting, timing and spectral characteristics of these objects can be explained with this model proposing rotating neutron stars with extremely strong magnetic fields in excess of 10^{14} Gauss. This strong magnetic field being proposed as the source of the energy required to explain the observed high luminosities. Indeed, persistent emission is found to be 1–3 orders of magnitude more luminous at X-ray energies below 10 keV, as well as for an apparently different non-thermal component above 10 keV, than the available spin-down energy. However, there is no agreed model scenario for the production of the high-energy emission in the magnetospheres of magnetars. In this review I will present the observational temporal and spectral characteristics at high-energies including new constraints on the production of the non-thermal emission above 10 keV.

Are the r-modes unstable in low-mass X-ray binaries?

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We consider the astrophysical constraints on the gravitational-wave driven r-mode instability in accreting neutron stars in low-mass X-ray binaries, in light of recent evidence for superfluidity/superconductivity from the young neutron star in the Cassiopeia A supernova remnant. We show that the observed population is such that several systems lie well inside the expected instability region, given the best current theoretical models. We discuss whether there is evidence that these systems really are unstable, or if it is the case that our theories are lacking in some respect. The likely answer is that our understanding of the many necessary areas of physics needs improvement, and we suggest several directions for future research.

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New synthetic evolution model of isolated neutron stars: from Main Sequence to dying

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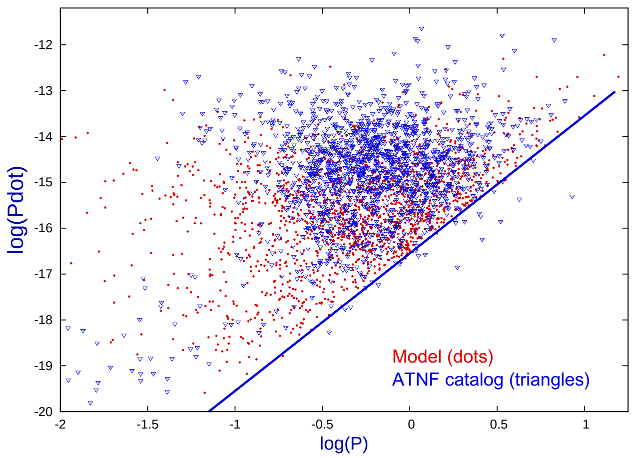

Figure 1: $P - \dot{P}$ diagram for the real (triangles) and model pulsars. Model pulsars are marked with small dots, while those in our with triangles. The thick solid line shows the modeled death line for pulsars.

We investigate the birth and evolution of isolated neutron stars (NS) in the whole volume of our Galaxy with our new code of NS population synthesis. We start modeling from the birth of massive OB stars and follow their evolution to supernova explosion. Next we integrate the equations of motion of the supernova remnants in the averaged Galaxy gravitational field for different NS birth space velocity distributions. We estimate the mean kick velocities by comparing the model Z-distribution of NS with that taken from ATNF pulsar catalogue [2]. The absolute one-dimensional velocity components are considered as normally distributed with a mean value of about 170 km/s.

In our model we take into account the significant magnetic field decay during the first million year of a NS life. Derived mean time of ohmic decay is $2.3 \cdot 10^5$ years. The rotational evolution of NS was analyzed with allowance for losses of their spin energy due to magnetic dipole braking. We model the subsample of galactic pulsars using the radio beaming model with inhomogeneous distribution of radio emission in the cone to obtain the correct fraction of detected pulsars. The distributions of pulsar periods P, time derivatives $\dot{P}$ and pulsar magnetic fields B appeared to be in a good agreement with those obtained with data from the catalogue [2]. We place the positions of all pulsars, which can be detected in our model with the Earth radio telescopes, on the $P - \dot{P}$ diagram as shown in Fig. 1. Our model can better fit the locations of pulsars on this diagram than the model [1] that neglects the field decay.

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Advancing to the third dimension: supernova models confronting observations

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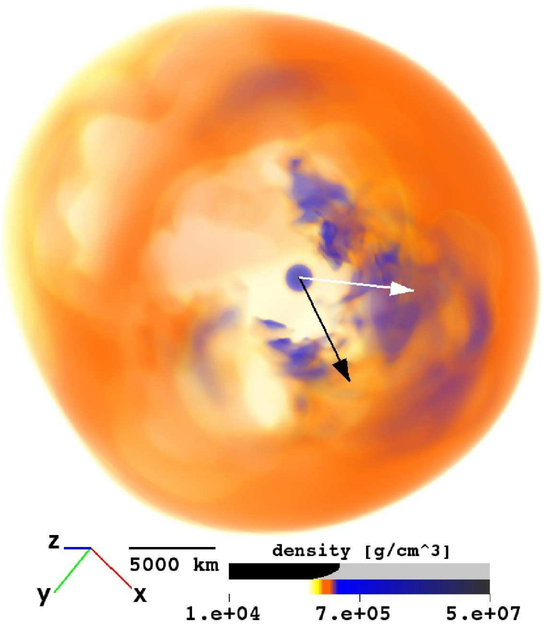

Figure 1: Mass-density distribution with directions of neutron star kick vector (white arrow) and spin vector for a three-dimensional simulation of a supernova explosion (from Refs. [1, 2]).

Gravitational collapse events and supernova explosions are generically multi-dimensional phenomena. This fact has been concluded for the first time from observations of Supernova 1987A, but all of its implications are recognized only as computational models of supernova explosions become increasingly more sophisticated and begin to be advanced to the third dimension and to longer evolution periods.

This talk will review our understanding of the physics and mechanism(s) of supernova explosions, also in view of possible links between progenitor stars and their explosions. Particular focus will be on the recent advances as well as challenges of three-dimensional hydrodynamic simulations. Implications of corresponding results for predictions of observable signals from supernovae and of properties of their gaseous and compact remnants (Fig. 1) will be discussed.

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Evidence for a varying disc–magnetosphere coupling in the 2008 outburst of SAX J1808.4–3658

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Accreting millisecond pulsars (AMPs) are unique laboratories for studying the physics of accretion disc-magnetosphere interaction in magnetized stars. In particular, it is important to understand how the neutron star magnetic field channels the accretion flow onto the stellar surface, because the nature of this interaction determines the properties of the X-ray emitting hotspots that produce the observed pulsations. Currently, the details of disc-magnetosphere coupling are not fully understood.

In a recent paper [1] we have shown that during the 2008 outburst of SAX J1808.4–3658, a major pulse profile transition was accompanied by simultaneous spectral changes involving a dramatic variation of the disc luminosity at almost constant total luminosity. As the constant total luminosity indicates a constant mass accretion rate, we interpret this transition as a change in the coupling between the neutron star magnetic field and the accretion disc. Specifically, we argue that variations in the size of the pulsar's magnetosphere influences the accretion curtain geometry. These variations affect the shape and the size of the hotspots, causing the observed pulse profile variations and also changing the disc luminosity and the total spectrum. Using this physical picture, we can self-consistently model the simultaneous pulse profile- and spectral transition.

We will also speculate on the physical origin of the transition, and discuss how a varying disc-magnetosphere coupling can: 1) affect the spin-up (spin down) torques during outbursts of AMPs, 2) be partly responsible for the "timing noise" in AMPs and 3) help to better constrain neutron star masses and radii by pulse profile modelling.

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New Optical/UV Counterparts and the Spectral Energy Distributions of Nearby, Thermally Emitting, Isolated Neutron Stars

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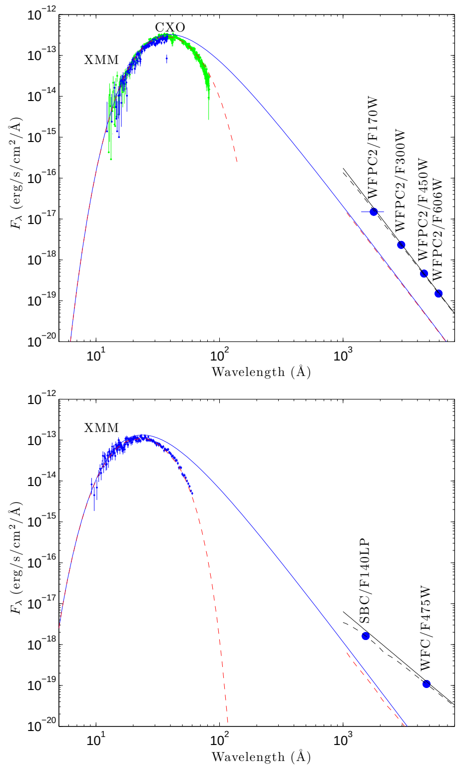

Figure 1: X-ray to optical SEDs of RX J1856.5–3754 (top) and RX J2143.0+0654 (bottom).

Seven of the nearby isolated neutron stars (INSs) known till date show predominantly thermal spectrum with $\sim 10^6$ K temperatures. Being relatively nearby and isolated makes them particularly attractive to constrain important NS properties such as mass, radius, cooling and possibly the equation of state of matter at ultra-high densities. However, interpreting their thermal spectra has turned out to be far more difficult than thought initially: The blackbody radius inferred from X-ray spectra, while ignoring optical/UV measurements, turns out to be too small to be a NS – even leading to immature speculations that the object might be a 'quark star'.

Therefore, we carried out HST observations of these INSs to identify their optical/UV counterparts. We now have clearly identified optical and UV counterparts to all seven INSs. When compared to their X-ray spectra, most of these sources appear to be brighter in optical/UV, in one case by a factor of 40! We find that the optical/UV spectral energy distributions (SEDs) show a range of slopes that are inconsistent with that expected from thermal (Rayleigh-Jeans) emission. We consider several explanations for this ranging from atmospheric effects, magnetospheric emission, and resonant scattering, but find that none is sufficient. These observations show that the puzzle of INSs, and possibly of all NSs, is far from over.

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Novel mechanism for the variation of braking index in young pulsars

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We study whether thermal evolution of young pulsars can affect their braking indices. We employ a model which assumes that a star possesses strong enough magnetic field with toroidal component so that toroidal magnetic flux tubes can pin neutron vortices. In the latter case glitches occur in the outer core, where the toroidal field is localized [1]. In our simplified model we assume that the star spins down due to the magnetic dipole braking. In that case the braking index should be equal to 3. However, as the star cools down a fraction of superfluid neutrons which is effectively decoupled from the rest of the star, increases. This affects the stellar dynamic properties, and, in particular, noticeably reduces the braking index. The indices calculated with account for such an effect agree well with observations of five young pulsars whose braking indices are the only reliably measured (ranged from 2 to 3 [2]).

The study was supported by the Dynasty foundation, Ministry of Education and Science of Russian Federation (contract 11.G34.31.0001), RFBR 11-02-00253-a, and FASI (grant NSh-3769.2010.2).

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Nearby, Thermally Emitting Neutron Stars

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I will discuss observational constraints on the properties and evolution of nearby, thermally emitting neutron stars. Combining X-ray spectroscopy and timing with optical photometry and astrometry, we are working to understand their origin and structure, but new observations continue to puzzle. I will review what we have learned and include results from recent optical and X-ray observations.

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Multiwavelength Observations of Pulsar Wind Nebulae

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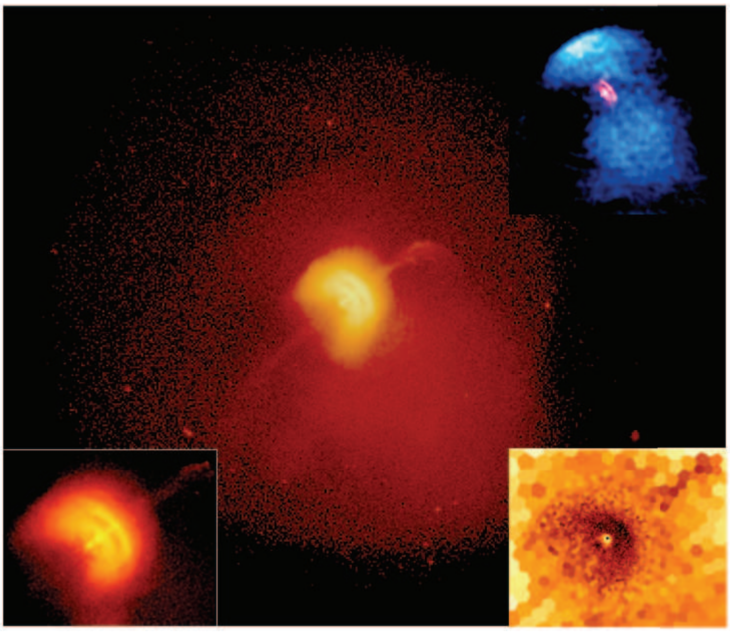

Figure 1: Vela PWN in X-rays (red, yellow) and radio(blue). *Chandra images* and an adaptively-binned spectral map of the inner PWN are shown. Radio image is obtained with ATCA.

Most of the pulsar rotational energy is lost via the wind comprised of relativistic particles and magnetic fields. The wind shocked in the ambient medium radiates emission observable from the radio through gamma-rays. X-ray observations proved to be particularly efficient in studying pulsar winds. Chandra and XMM-Newton have discovered ∼100 pulsar-wind nebulae (PWNe) with very different appearances, spectra and luminosities. A fraction of these PWNe have been also detected in TeV and GeV gamma-rays and/or at the radio and optical wavelengths. The morphology, multiwavelength spectrum, and radiative efficiency of a PWN depend on the angular distribution, magnetization and energy spectrum of the unshocked wind, particle acceleration mechanism, pulsar velocity and properties of the ambient medium. We will overview and summarize recent observational results on PWNe and pulsars, paying special attention to the cases where the observational results challenge our current understanding of pulsar winds. Among the highlights are spatially-resolved spectroscopy in X-rays (see Fig. 1) and correlations between the X-ray/GeV/TeV properties and pulsar spin-down parameters as well as implications for pulsar-wind models.

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Magnetar asteroseismology with long-term gravitational waves

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Magnetic flares and induced oscillations of magnetars (super-magnetized neutron stars) are promising sources of gravitational waves (GWs). We suggest [1] that the GW emission, if any, would last longer than the observed X-ray quasi-periodic oscillations (X-QPOs), calling for the longer-term GW analyses from a day to months than the current searches. Like the pulsar timing, the oscillation frequency would also evolve with time because of the decay or reconfiguration of magnetic field, which is crucial for the GW detection. With the observed GW frequency and its time-derivatives, we can probe the interior magnetic field strength and its evolution to open a new GW asteroseismology with the next generation interferometers like advanced LIGO, advanced VIRGO, LCGT and ET.

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The Radio Pulsar/Magnetar Connection

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Neutron stars today are recognized as having multiple different observational manifestations, with the connections among the different classes still poorly understood. The class of objects thought to be "magnetars" shows the most dramatic behavior, with strong X-and γ-ray bursts and often enhanced pulsed and unpulsed emission, particularly in the X-ray band. However spin-inferred magnetic fields of magnetars are often comparable to, and sometimes less than, those inferred in otherwise conventional radio pulsars. Here we consider the highest magnetic field radio pulsars, in an effort to identify evidence for magnetar-like behavior that would help unify, both observationally and physically, the two classes of objects. In particular we report on deep X-ray observations of several young, high-magnetic field pulsars that suggest they are hotter than lower-field pulsars of the same age [3]. We also report on the aftermath of a magnetar-like outburst seen in 2006 from the apparently rotation-powered pulsar J1846–0258 [1], showing that the spin properties of the pulsar remain significantly altered in spite of its much faster radiative recovery [2].

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The true nature of seven enigmatic faint persistent slow X-ray pulsators

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The faint persistent slow X-ray pulsars form an unusual class of accreting neutron stars with high mass companion stars, which have long orbital periods (> 30 days) and low eccentricities. These sources are expected to be formed in a different type of supernova explosion than the neutron stars present in the classical, transient Be/ X-ray binaries. Till now there are only 4 such systems known to be present and thus inspired us to find more in this class. Our sample include seven sources with similar X-ray properties to the four sources already known. Our *Chandra* and *XMM-Newton* observations of these seven sources helped us to find their positions with the sub-arc resolution and to study their spectral and timing properties. The near-infrared (NIR) counterparts were identified using the ESO-NTT observations. Our near-infrared spectral observations using the ESO-VLT helped us to further constrain their nature. We used the previously obtained *ASCA* and *BeppoSAX* observations of the sources to study the possible correlation in spectral, pulse properties and luminosity variations. In this talk, we discuss our results in the light of the neutron-star formation mechanism and how our targets have gained new insight in this matter.

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Observations of accreting pulsars with Konus-Wind

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The Konus gamma-ray burst experiment on board the Global Geospace Science (GGS) Wind spacecraft has been successfully operating since 1994, November. In interplanetary space far outside the Earth's magnetosphere, Konus-Wind benefits from continuous coverage uninterrupted by Earth occultation and an exceptionally stable background. Two omnidirectional detectors allow Konus-Wind to operate as a full-time, all-sky monitor for transients in hard X-ray/soft gamma-ray band. In addition, it has provided unprecedented continuous monitoring of pulsed sources above ∼20 keV in the course of the mission. We demonstrate the possibility of studying accretion-powered pulsars using the Konus-Wind background data. As an example of such a study we present the results of long-term monitoring of the transient Be/X-ray binary pulsar system A 0535+26. We report on measurements of the pulsed flux, spin frequency, hardness ratio, and folded pulse profiles history during Type I and Type II outbursts over 16 years of observations.

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Statistics of magnetic field of massive stars, white dwarfs and neutron stars

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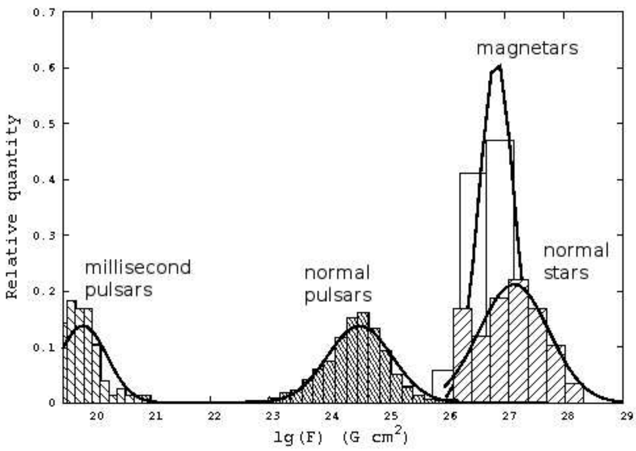

Figure 1: Distributions of magnetic fluxes for massive OB stars, millisecond pulsars, normal pulsars and magnetars [1]. Thick lines show their fit with the log-normal law.

Statistical properties of mean magnetic fields $\mathcal{B}$ of OB stars, white dwarfs and neutron stars (NSs) and their magnetic fluxes are investigated based on the newest field measurements. The magnetic field distribution function $F(\mathcal{B})$ for massive OB stars is determined. The sharp decrease of $F(\mathcal{B})$ for magnetic fields with *rms* mean value of $\mathcal{B} < 300$ G is found. We estimate the magnetic fluxes $\mathcal{F}$ of studied objects and establish that distribution of magnetic fluxes for all of them can be described with the log.-normal function shown in Fig. 1.

For massive stars with measured magnetic fields their magnetic fluxes has mean $\log(\mathcal{F}) = 27.7$. The mean magnetic fluxes for a whole ensemble of Galactic NSs are much smaller with a mean value of $\log(\mathcal{F}) = 24.5$. A special case is provided by millisecond pulsars with relatively small magnetic fluxes and a mean $\log(\mathcal{F}) = 19.80$. On the other hand, the distribution of magnetic fluxes for magnetars is close to that for OB stars. We discuss a possible explanation of large defference of magnetic fluxes of normal and neutron stars for various scenarios of the magnetic field formation for NSs. We investigate the impact of the relatively small number of OB stars with *rms* magnetic field $\mathcal{B} < 300$ G on the distribution over magnetic fluxes of NSs.

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A likely optical counterpart of the PSR J1357−6429

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We present the results of deep optical observations of a young PSR J1357−6429 with the ESO/VLT in *VRI* bands. The pulsar has been recently discovered in the radio frequency range [2] and then observed in the X-rays [1, 3].

We report an optical detection of a faint counterpart candidate of the pulsar in all three V, R and I bands. The candidate position coincides with the X-ray position of the pulsar at $\approx 0''.5$ ($1\ \sigma$) accuracy level. The candidate has unusual colours, as compared to ordinary stars. This can be considered as an additional evidence of its pulsar nature.

We discuss the optical–X-ray spectral energy distribution of the PSR J1357−6429 and compare it with those of other pulsars detected in the optical range.

This work was supported in part by the Ministry of Education and Science of the Russian Federation (contract 11.G34.31.0001).

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Multi-wavelength emission region of gamma-ray emitting pulsars

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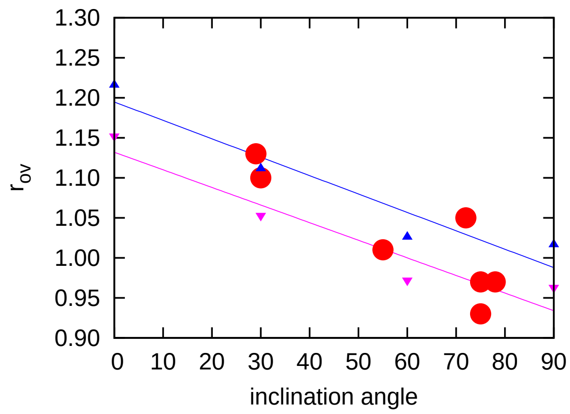

Figure 1: The relation between altitude parameter r_{ov} and inclination angle. The fitting samples are shown as red circles. The altitudes corresponding to the separatrix layer model [2] are shown as purple downward ($r_{ov,ff} = 0.90$) and blue upward triangles ($r_{ov,ff} = 0.95$). The two lines are linear fitting lines for the separatrix layer model.

Using the outer gap model, we investigate the emission region for the multi-wavelength light curve of energetic pulsars. Following the model of Takata et al. (2008), we assume that γ-ray and non-thermal X-ray photons are emitted from a particle acceleration region in the outer magnetosphere, and UV/optical photons originate above that region. We assume that γ-rays are radiated only by outwardly moving particles, whereas the other photons are produced by particles moving inward and outward. We parameterize the altitude of the emission region and determine it from the observed multi-wavelength pulse profile using the observationally constrained magnetic dipole inclination angle and viewing angle of the pulsars. We find that the outer gap model can explain the multi-wavelength pulse behavior by a simple distribution of emissivity, and discuss the possibility of further improvement. From observational fitting, we also find a general tendency for the altitude of the γ-ray emission region to depend on the inclination angle. This tendency is similarly found for the force-free magnetosphere (Fig. 1).

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Contribution of longitudinal plasmons to thermodynamics of dense electron plasma

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We study plasma effects on thermodynamics of equilibrium electromagnetic radiation in dense electron plasma of arbitrary degeneracy. At temperatures close to the plasma temperature the significant contribution arises from the longitudinal plasma waves. In the non-relativistic plasma this contribution dominates over the contribution from transverse photons due to the factor $(c/v_e)^3$ which comes from the plasmon occupation number (v_e is electron velocity). Applications of these results to radiation transfer in neutron star envelopes are discussed.

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Theory and Simulations of Pulsar Wind Nebulae

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Since the pioneering work by Rees & Gunn (1974) and Kennel & Coroniti (1984) the relativistic MHD theory of pulsar wind nebulae has gradually become widely accepted by the astrophysical community. The discovery of approximately axisymmetric jet-torus structure of the Crab Nebula stimulated the transition from the spherically-symmetric models to models with axial symmetry of the pulsar wind. The rapid development of numerical methods for relativistic MHD in recent years has allowed exploring this model to a great depth via computer simulations. Their results revealed complicated highly dynamic flow inside the plerion with a number of very attractive properties which allow one to explain not only the observed large-scale structure of the Crab Nebula but also its fine features, such as wisps and the bright inner knot. The model, however, requires the pulsar wind to be particle dominated whereas the theory of pulsar winds clearly favours the Poynting-dominated regime. A number of ideas have been put forward to resolve this controversy. These include dissipation of the MHD wave component of the wind along the way to the termination shock and at the termination shock, as well as revision of the theory of particle production in pulsar magnetospheres. The recently discovered gamma-ray flaring of Crab Nebula is another challenge. The flares do not seem to be associated with any bright compact features of the nebula as seen in X-rays and optics and suggest ongoing magnetic reconnection inside the Crab plerion.

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Low-frequency radio emission at acceleration of electrons in a vacuum gap of a pulsar

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It is shown that the powerful low-frequency radiation, which is responsible for the radio emission of pulsars, appears when electrons are accelerated in a vacuum gap with the electric field vanishing at the surface of the star. This radiation may be responsible both for normal and giant pulses of the pulsars. Due to continuous pumping during electron acceleration the energy density of the low-frequency radiation in the gap may be quite high which leads to gamma radiation by the inverse Compton effect. This allows us to relate the gamma radiation, observed at the Fermi LAT [1] and correlated with giant pulses, with the radiation of the particles accelerated in the inner vacuum gap. Averaging over the polar cap leads to a power-law spectrum of pulsar radio emission. We have found analytically the position of the high frequency cutoff [3] in the radio spectra, have estimated the power of radio emission and the location of the low frequency turnover, as well as the behavior of the electric field in the gap. We propose also an explanation for the significant changes in the intensity of the main pulse and interpulse [2] in the discussed frequency range for the Crab pulsar.

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What kind of fission is more important in the r-process?

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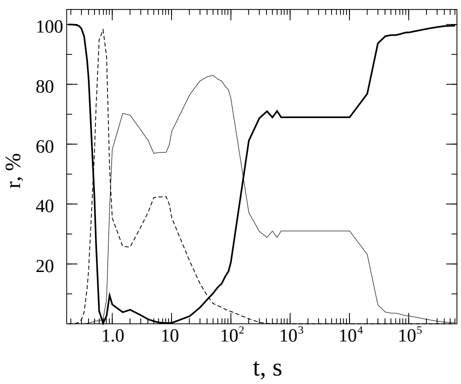

Figure 1: The instantaneous strength of different kinds of fission scaled to 100%: thick – spontaneous, dashed – neutron-induced, and thin – beta-delayed.

The formation of heavy elements in the scenario of neutron star mergers [1] with rather long duration of the r-process is sufficiently intensive, which leads to the fast exhaustion of seed nuclei. The nucleosynthesis wave approaches the actinoid region, where fission becomes the main reaction channel. Fission products participate in the r-process as seeds again, thus forming a quasisteady nucleus flow. With the neutron density decrease, the r-process turns into the n-process and heavy elements return to the stable region by means of consistent beta-decays and fission. The proposed r-process model applied to the scenario of neutron star mergers describes well observed abundances of heavy elements with A > 100, which confirms the formation of these elements in the main r-process. The formation of superheavy elements is possible, but their survival depends on nuclear parameter estimates, including the lifetimes of long-lived superheavy isotopes.

Up-to-date neutron-induced [2], beta-delayed [3] and spontaneous [4] fission rates were used, along with fission fragment mass distribution [5]. The contributions of neutron-induced, beta-delayed and spontaneous fission during the main r-process were obtained as part of this work (see Fig. 1). It shows that spontaneous fission prevails at quasisteady nucleus flow stage, while neutron-induced fission dominates at the end of the r-process. The latter turns slowly into beta-delayed fission in the n-process. Finally, superheavy products decay via spontaneous fission and alpha-decay. Thus all fissions are significant for the main r-process scenario (with neutron-rich environment), but exact contributions depend on astrophysical scenario and nuclear data.

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Physical features of binary Coulomb crystals

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Thermodynamic functions of a Coulomb crystal composed of two types of ions with a uniform electron background are studied using harmonic lattice approximation. Simple cubic lattice with two ions in the primitive cell and hexagonal close packed lattice are considered. An analysis of the phonon spectra shows that these binary Coulomb crystals are stable, if the ratio $\alpha = Z_1^2 M_2/Z_2^2/M_1$ is not too large (Z_i and M_i are the i-th ion charge number and mass; ion numbers 1 and 2 are chosen so that $\alpha > 1$). The thermodynamic functions are obtained by numerical integration over the respective Brillouin zones with relative accuracy of the results $\sim 10^{-4}$. Quantum and classic limits of the thermodynamic functions are analyzed, and the applicability of the linear mixing rule to such crystalline Coulomb mixtures in various regimes is discussed.

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Dirac neutrino magnetic moment and a possible time evolution of the neutrino signal from a supernova

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We analyze the influence of neutrino helicity conversion, $\nu_L \to \nu_R$, caused by the interaction of the Dirac neutrino magnetic moment with a magnetic field, on the neutrino flux from a supernova. We show that if the neutrino has a magnetic moment in the range $10^{-13}\,\mu_{\rm B} < \mu_\nu < 10^{-12}\,\mu_{\rm B}$ and a magnetic field of $\sim 10^{13} - 10^{14}$ G is present in the supernova envelope, a peculiar kind of time evolution of the neutrino signal from the supernova can appear due to the resonance transition $\nu_L \to \nu_R$ in the magnetic field of the envelope. If a magnetar with a poloidal magnetic field is formed in a supernova explosion, then the neutrino signal could have a pulsating behavior. In other words, a kind of a neutrino pulsar could be observed, if magnetar rotates around an axis that does not coincide with its magnetic moment and if the orientation of its rotation axis is favourable for our observation.

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"Invisible" Magnetic Fields of Pulsars and Magnetars: Observational Constraints, Hall Cascade and Crust Breaking

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We will present two related recent works on the magnetic fields of isolated neutron stars (NSs): (i) How do features of light curves (time asymmetry and pulse fraction) observed in some NSs constrain the subsurface magnetic field strength and structure? (ii) Crustal magnetic field evolution due to current sheet formation (driven by Hall drift): enhanced Ohmic dissipation vs crust breaking. The outcome may explain the different behaviors of pulsars and magnetars.

Magnetic Field Instabilities in Strongly Magnetized Neutron Stars

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The internal topology, strength and dynamics of magnetic fields in strongly magnetized neutron stars play a crucial role in the generation of recurrent flaring events. Despite this, very little is known about the internal magnetic field structure of these exotic objects. I will present ongoing work on modeling neutron star magnetic fields utilizing a three-dimensional, general relativistic magnetohydrodynamics code. I will discuss the onset and nature of various magnetic field instabilities and their relevance for flare generation, as well as ongoing efforts to determine stable magnetic field configurations for the interior region of the star.

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News on Thermonuclear X-ray Bursts From Terzan 5 and Circinus X-1

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The neutron star transient and 11 Hz X-ray pulsar IGR J17480–2446, recently discovered in the globular cluster Terzan 5, showed unprecedented bursting activity during its 2010 October-November outburst. We analyzed all X-ray bursts detected with the Rossi X-ray Timing Explorer and find strong evidence that they all have a thermonuclear origin, despite the fact that many do not show the canonical spectral softening along the decay imprinted on type I X-ray bursts by the cooling of the neutron star photosphere. We also find that the peak burst to persistent luminosity ratio determines whether or not cooling is present in the bursts from IGR J17480–2446, and argue that the apparent lack of cooling is due to the "non-cooling" bursts having both a lower peak temperature and a higher non-burst (persistent) emission. We conclude that the detection of cooling along the decay is a sufficient, but not a necessary condition to identify an X-ray burst as thermonuclear, and compare these findings with X-ray bursts from other rapidly accreting neutron stars.

We also report the detection of 15 X-ray bursts with RXTE and Swift observations of the peculiar X-ray binary Circinus X-1 (Cir X-1) during its 2010 May X-ray rebrightening. These are the first X-ray bursts observed from the source after the initial discovery by Tennant and collaborators, 25 years ago. We obtain an arcsecond location of the bursts that confirms once and for all the identification of Cir X-1 as a type I X-ray burst source, and therefore as a low magnetic field accreting neutron star. We put forward a scenario to explain why Cir X-1 shows thermonuclear bursts now but not in the past, when it was extensively observed and accreting at a similar rate.

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Accretion in the Magnetic Propeller Regime

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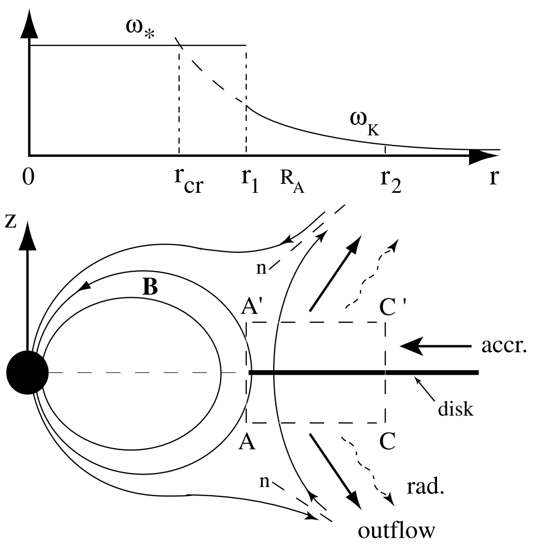

Figure 1: Propeller regime of accretion. Top panel shows the angular velocity of the equatorial matter and the bottom shows the magnetic field.

We consider disk accretion to rotating magnetized stars in the 'propeller' regime. This is roughly the regime where the radius of the star's magnetosphere $R_A \propto \mu^{4/7}/\dot{M}^{2/7}$ is larger than the corotation radius $r_{cr} = (GM/\Omega_*^2)^{1/2}$, where Ω_* is the angular rotation rate of the star and M is its mass, μ is its magnetic moment, and $\dot{M}$ is the accretion rate [1, 2]. We have studied accretion in this regime using axisymmetric MHD simulations which include an α_ν viscosity and an α_d magnetic diffusivity and which assume symmetry about the equatorial plane [3, 4]. Accretion to the star is found to be strongly episodic with matter accumulating near the magnetosphere and then plunging onto the star with a quasi-period of the order of $100(2\pi/\Omega_*)$ [4]. Outflows of matter and angular momentum in conical winds are also strongly episodic and they cause a rapid spin-down of the star [3, 4]. More recently we have studied accretion in the propeller regime using axisymmetric MHD simulations with a high resolution grid covering the disk in order to resolve the turbulence arising from the magneto-rotational instability (no α's) and no assumption of symmetry about the equatorial plane. We again find strongly episodic accretion with the plasma flowing close to the star along field lines in one or the other hemisphere while an outflow of matter and angular momentum occurs in the opposite hemisphere. This broken symmetry was also found in earlier simulations [6].

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Determination of fundamental parameters of neutron star in MXB 1728–34 from fitting of burst spectra by the ATM model atmospheres

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We analyzed burst spectra of MXB 1728-34 obtained by RXTE PCA instrument during the period 1996-2005. We selected 14 spectra integrated by 0.25 second at the very end of bursts, when we expected that the atmosphere regained the hydrostatic equilibrium. A large grid of redshifted model spectra of hot neutron stars with effective temperatures T_{eff}=10-30 mln K and log(g) from 15.0 down to critical gravity was fitted to each our spectrum. The gravitational redshift (z) of theoretical models was varied in the range from 0.00 to 0.60. We investigated three chemical compositions: hydrogen-helium atmosphere (N_{He}/N_H=0.11), atmosphere with solar iron abundance (N_{He}/N_H=0.11 and $N_{Fe}/N_H = 10^{-5}$) and with 100 times larger iron number abundance.

The best fits were obtained for model atmospheres with iron abundance 100 times larger than the solar iron abundance. For these models we obtained the following ranges of neutron star parameters at 1-σ confidence level: z=0.10-0.44 and log(g)=14.2-14.8. Assuming that the whole surface of the star radiates in X-rays we obtain mass M=0.266-1.354 $M_\odot$ and radius R=3.605-8.836 km. These values are consistent with strange matter equation of state. However, ranges of M and R obtained at 2- and 3-σ confidence levels do not exclude equations of state of normal matter.

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New observation of three AXPs at low radio frequencies

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Anomalous X-ray pulsars - AXPs are a group of 9 X-ray sources showing periodical pulsations at periods in the 2-12 s range. The main problem is the source of energy, because their X-ray luminosities are much higher than can be provided by the rotational kinetic-energy losses. Many attempts have been made to detect radio emission. The first detection of periodical pulsations from the AXP 1E 2259+586 have been made at the frequency 111 MHz by Malofeev [1, 2]. The second transient AXP XTE J1810-197 and the third AXP candidate 1E1547.0-5408 [3, 4] have been detected in the wide frequency band 0.69-42 GHz. In this report we present new data for three AXPs 1E 2259+586, 4U 0142+61 and XTE J1810-197 at low frequencies. The observations were carried out on two sensitive transit radio telescopes in the range 42-112 MHz. The flux densities and mean pulse profiles, the estimation of the distances and integrated radio luminosities are presented. We used new digital receivers to obtain pulse profiles and dynamic spectra. Comparison with X-ray data shows large differences in the mean pulse widths and luminosities.

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Do "magnetars" really exist?

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First of all we can declare that magnetodipole model giving magnetic fields for AXPs and SGRs $B \sim 10^{14} - 10^{15}$ is not correct even for normal pulsars [1] and for AXPs and SGRs as well [2].

Secondly, we must answer the question: what does the word "magnetar" mean [3]?

1) Does it mean the supercritical dipole magnetic field? But magnetic field of SGR 0418+5729 is less than 7.5×10^{12} G. 2) Is it the bursting behaviour? Normal pulsars have the burst components [4] and giant pulses. 3) Does it mean that the rotational power is low compared to the X-ray luminosity? The young pulsar PSR J1846-0258 in the SNR Kes 75 ($\tau = 884$ years), $P = 326$ msec shows X-ray bursts similar to AXPs and SGRs. However its X-ray luminosity $L_x = 4.1 \times 10^{34}$ erg/sec can be provided by the losses of the rotation energy $dE/dt = 8.1 \times 10^{36}$ erg/sec. 4) Is it the black body plus power-law X-ray spectrum? Normal radio pulsars emit thermal and non-thermal radiation outside the radio range. 5) Is it the erratic radio pulse behaviour? Individual pulses of radio pulsars have different forms and spectra.

So, there is no single criterion defining the magnetar type.

We believe that all types of isolated pulsars can be described on the basis of the assumption that conventional neutron stars ($P \leq 1$ sec, $B_s = 10^{11} - 10^{13}$ G) are their basic bodies. We put forward the drift model [5] for an explanation of peculiarities of anomalous pulsars.

In the framework of the drift model we estimate, for example, for PSR J1642-4950 $P = 0.32$ sec, $dP/dt = 6.29 \times 10^{-13}$, $\lg B_s = 12.53$. In this model, the angle β between the rotation axis and the magnetic moment must be small. Indeed, our calculations have shown that in PSR J1642-4950 $\beta = 15,6°$, while in AXP J1810-197 and 1E 1547.0-5408 $\beta < 20°$.

The main problem of the drift model is the difficulty in explaining the giant gamma-ray bursts in SGRs. However this difficulty is common for all known models. We believe that in any model some kind of plasma injection from the inner layers of neutron stars and thermonuclear reactions in their magnetospheres must be suggested.

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Average pulse profiles at frequencies 102 and 111 MHz and spectra of radio pulsars

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Average profiles for several, mostly weak, pulsars at 102 and 111 MHz are presented. Pulse shapes have been obtained for the first time for most of the weak pulsars (about 50% of the total sample). A comparison with high-frequency data (mostly at 234, 408, 610, 925 and 1408 MHz) demonstrated appreciable changes in the pulse width and shape depending on frequency. For majority of the pulsars, the number of components is preserved, but the intensities of individual components can change. As a rule, the pulse width increases with the decrease of the frequency.

The flux densities of more than 200 pulsars have been obtained at frequency 102 MHz. Using these data, a catalogue of more than 300 "normal" pulsars has been created by Malofeev [1]. We found that the majority of spectra of the "normal" pulsars have the low-frequency turn-over, but spectra of millisecond pulsars do not. It means that "normal" and millisecond pulsars have different mechanisms of pulsed emission generation.

We have concluded that the observed emission can be generated at cyclotron frequencies.

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X-ray luminosity function of rotation-powered pulsars

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We present the calculations of the X-ray luminosity function of rotation-powered pulsars. The luminosity function was calculated in two different ways: using Monte Carlo simulations and using an analytical model describing the evolution of pulsars for various birth rotation periods and magnetic field distribution functions. In our simulations we used the recent observational results on the dependence of the radiative X-ray efficiency on the characteristic age of the pulsars [1], which implies a higher number of young bright pulsars. We show that the X-ray luminosity function has a slope, which is similar to the observed X-ray luminosity function obtained by Grimm et al. [2]. We discuss possible contribution of the rotation-powered pulsars to the observed X-ray luminosity function and the connection between the young rotation-powered pulsars and ultra-luminous X-ray sources.

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X-ray and optical observations of the closest isolated radio pulsar

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We report on the first deep X-ray and optical observations of PSR J2144–3933, the closest isolated radio pulsar currently known. This is also the slowest (P = 8.51 s) and least energetic ($\dot{E}_{rot} = 2.6\times10^{28}$ erg s^{-1}) radio pulsar and it is located in the period-period derivative diagram far beyond the typical radio 'death lines'. Thanks to a precisely measured parallactic distance (170 pc), the X-ray and optical data can set robust constraints on the surface temperature of this old neutron star.

Magnetorotational mechanism of core-collapse supernova explosion

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The magnetorotational (MR) mechanism of core collapse supernova explosion is discussed. Results of 2D simulations of MR mechanism of supernova explosions show that differential rotation of the collapsed core leads to the amplification of the toroidal component of the magnetic field. At the initial stage it grows linearly with time but due to magnetorotional instability all components of the magnetic field start to grow exponentially. MR supernovae are asymmetrical. MR mechanism of core collapse can explain asymmetrical jets in supernova explosions. We compare results of MR supernova explosion simulations for different equations of state.

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Spectral and photometric monitoring of CCSNe at SAO RAS

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This work briefly describes the aims, methods and first results of the observational program of distant core-collapse supernovae (SNe) study. This work is done within the framework of an international cooperation program on the SNe monitoring at the 6-m BTA, 1-m Zeiss telescopes of the SAO RAS, and > 10 telescopes of USA, Italy, Spain, India, Russia, etc. [1].

We study both the early phases of events (SN type determination, redshift estimation, and a search for manifestations of a wind envelope) and the nebular phase (the effects of explosion asymmetry). The SNe, associated with cosmic gamma-ray bursts are of particular interest [2–5]. An interpretation of our observational data along with the data obtained with other telescopes is used to test existing theoretical models of both the SN explosion and the surrounding circumstellar medium.

The number of events expected and accessible for observations at the SAO is 1–2 events per week. The classification of objects as core-collapse SNe is possible from colors as early as at the detection stage. A large telescope is needed to achieve the required quality of data, as the expected apparent magnitudes of objects vary from 15^m to 25^m.

In 2009–2010 44 objects were observed, and for 12 newly detected SN candidates we determined the types, the phases after maximum, and redshifts. The discovery of two more SNe was confirmed photometrically. We completed the study of five SNe: 2008gz [6], 2008in, 2009bw, 2009ay, 2009de, three more objects (SNe 2008iy, 2009jf, 2010jl) are currently monitored . We are planning to observe the host galaxies of SNe 2009de and 2008iy.

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Relativistic kinetic equation for Compton scattering of polarized radiation in a strong magnetic field

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Relativistic kinetic equation for Compton scattering of polarized radiation in a strong magnetic field is deduced using Bogolyubov's method. Induced scattering and the Pauli principle are taken into account. Polarization of electron gas is taken into account as well in the common form of the kinetic equation. Special forms of equation for the cases of non-polarized electrons, rarefied electron gas and two-mode distribution of radiation are found. Results can be useful for construction of models of atmospheres and magnetospheres of neutron stars.

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Radio Polarization Measurements of the Longest Pulsar Trail G315.9−0.0

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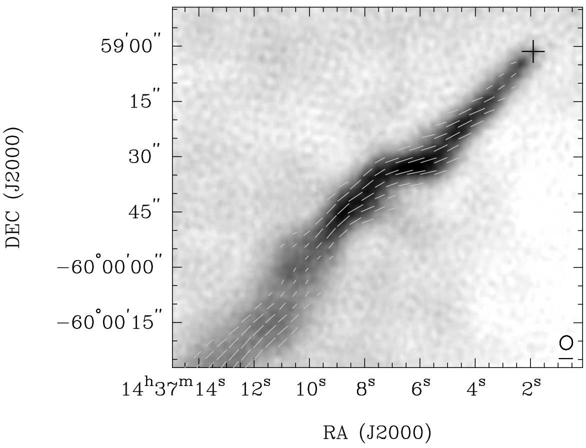

Figure 1: Radio continuum image of G3159−0.0 at 6 cm overlaid with the intrinsic polarization B-vectors (i.e. after correction for Faraday rotation). Location of pulsar J1437−5959 is marked by the cross.

Pulsars lose a significant amount of their rotational energy through relativistic winds. The consequent interactions of the winds with the ambient medium result in broadband synchrotron emission known as pulsar wind nebulae (PWNe). Radio polarization measurements of PWNe can provide a powerful probe of the magnetic field structure, offering important information for understanding the particle acceleration process in the termination shock, and revealing the physical conditions of the interstellar medium.

We present new radio polarization observations of the 'Frying Pan' Nebula (G315.9−0.0) at 3 and 6 cm taken with the Australia Telescope Compact Array. Powered by the energetic pulsar J1437−5959 [1], this highly collimated bow-shock PWN extends over 20 pc, the longest pulsar trail ever observed in radio. We found that the PWN is highly polarized, with the intrinsic magnetic field well aligned along the trail, similar to the case of the Mouse PWN [2]. A kink is observed at $1'$ (~ 2 pc) downstream from the pulsar, which we believe is due to turbulence of the interstellar medium. We also found evidence of spectral softening along the PWN, with a changing power-law index α ($S_\nu \propto \nu^\alpha$) from −0.1 near the pulsar position to ≤ -0.5 downstream.

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On the structure of pulsar magnetosphere

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There are some known theoretical models used for investigations of pulsars at present. One of the most important parameters for the verification of these models is the angle β between the axis of the emission cone (the direction of the magnetic moment vector) and the pulsar rotation axis. The estimations of the angle β have been carried out in two ways (yielding β_1 and β_2). They are based on some statistical relationships. Analysis of the structure of the pulsar magnetospheres was based on estimates of the angles β for pulsar samples from the articles [1, 2]. We have used pulse profiles for the first approach and monotonous behavior of a position angle for the second one. It is sufficient to take values of W_{10} from catalogues.

283 pulsars at the wavelength of 20 cm and 132 pulsars at the wavelength of 10 cm from [1] and 80 objects from [2] were selected for the analysis by the first method. For the analysis by the second method we have used 40 pulsars at the wavelength of 20 cm and 31 pulsars at 10 cm from [1] and 34 objects from [2]. Since the position angle behavior is measured not for all pulsars and measurements were taken only within the main pulse, the number of pulsars for estimation of the angle β by the second method is much smaller.

Calculations of the first type are based on the assumption that the line of sight passes through the center of the emission cone. For these samples we have low mean values ($\langle\beta_1\rangle = 18^\circ$ at λ=10 cm, $\langle\beta_1\rangle = 14^\circ$ at λ=20 cm and $\langle\beta_1\rangle = 27^\circ$ for 800-950 MHz) which are close to each other. For several dozens of pulsars the estimates of β_2 are made for an arbitrary orientation of the line of sight and for two signs of maximum derivatives C of the position angles. The mean values of such angles are $\langle\beta_2\rangle = 33.9^\circ$ (10 cm, $C > 0$) and $\langle\beta_2\rangle = 52.1^\circ$ (10 cm, $C < 0$), $\langle\beta_2\rangle = 33.9^\circ$ (20 cm, $C > 0$), $\langle\beta_2\rangle = 54.1^\circ$ (20 cm, $C < 0$), $\langle\beta_2\rangle = 36.4^\circ$ (800-950 MHz, $C > 0$) and $\langle\beta_2\rangle = 49.1^\circ$ (800-950 MHz, $C < 0$). These values are very close to each other. The common average is $\langle\beta_2\rangle = 43.5^\circ$. The dependence $W(P) \sim P^{-0.25}$ obtained in this work differs from the usually used $W(P) \sim P^{-0.5}$. This can be explained by the rate of the growth of plasma instabilities near the surface of the neutron star. The quadrupole component of the magnetic field does not play a key role.

We did not detect any relationship between values of β and pulsar ages (z-distances, luminosities L and characteristic ages $\tau = P/(2\mathrm{d}P/\mathrm{d}t)$).

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Relativistic numerical models for stationary superfluid neutron stars

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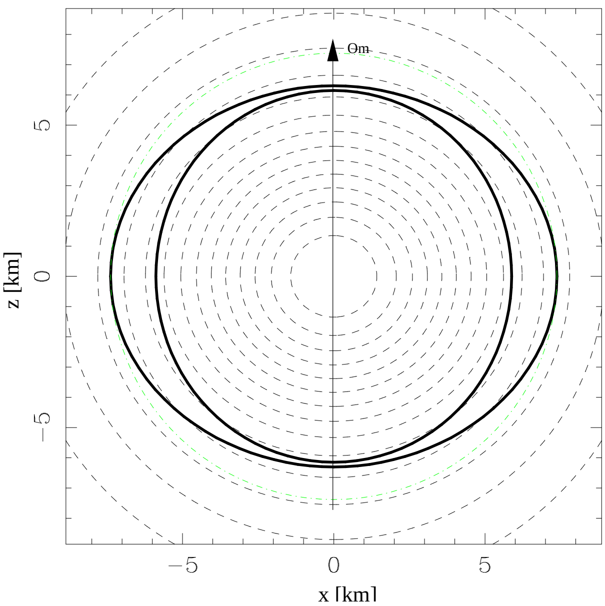

Figure 1: Meridional cross-section of an oblate-prolate two-fluid configuration. The dotted lines represent lines of constant "gravitational potential" N, while the thick lines are the respective surfaces of the neutron- and proton fluids (from Ref.[1]).

We have developed a model and a numerical code for stationary rotating superfluid neutron stars in full general relativity. The underlying two-fluid model is based on Carter's covariant multi-fluid hydrodynamic formalism. The two fluids, representing the superfluid neutrons on one hand, and the protons and electrons on the other, are restricted to uniform rotation around a common axis, but are allowed to have different rotation rates. We have performed extensive tests of the numerical code, including quantitative comparisons to previous approximate results for these models. The results presented here are the first "exact" calculations of such models in the sense that no approximations (other than that inherent in a discretized numerical treatment) are used. Using this code we reconfirm the existence of prolate-oblate shaped configurations. We studied the dependence of the Kepler rotation limit and of the mass-density relation on the relative rotation rate. We further demonstrate how one can simulate a (albeit fluid) neutron-star "crust" by letting one fluid extend further outwards than the other, which results in interesting cases where the Kepler limit is actually determined by the outermost but *slower* fluid.

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Collective excitations in the neutron star crust

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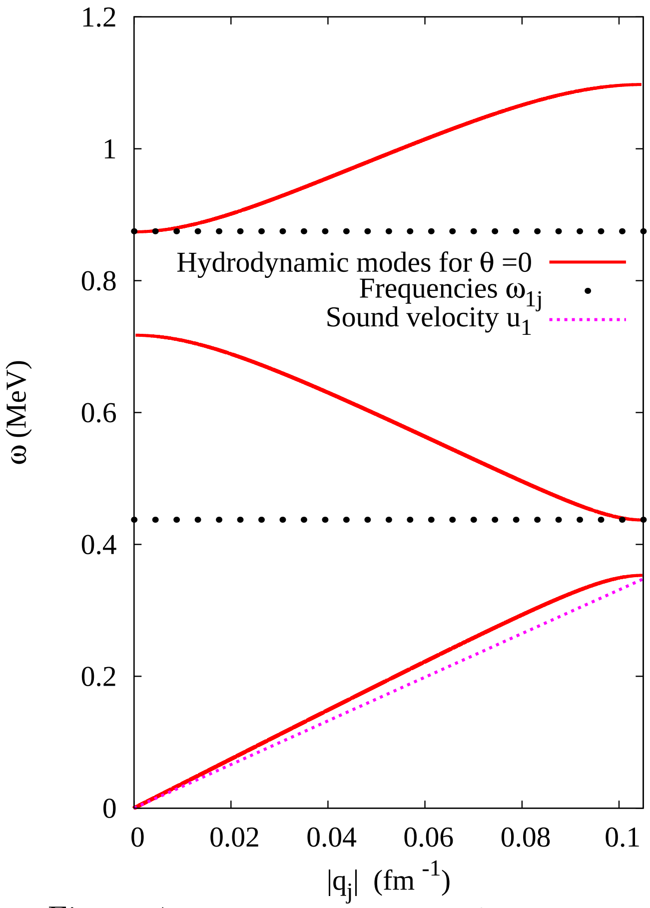

Figure 1: Dispersion relation for excitations in the neutron star inner crust at a baryon density of $n_B = 0.0013\,\mathrm{fm}^{-3}$.

It has been known for a very long time that within the different structures inside a neutron star we can find superfluid and superconducting ones. The first observational indications were the glitches, and more recently observations of the surface thermal emission have been discussed in this context. The latter is an observable, which depends on the heat transport properties, and is thus very sensitive to the superfluid and superconducting character of the different structures inside the star. The presentation is focused on the inhomogeneous "pasta phases" in the inner crust. The spectrum of collective excitations will be discussed within a superfluid hydrodynamics approach. An example of the results is shown in Fig. 1. The advantage of the approach is that the wavelengths are not limited to the size of the Wigner-Seitz cell as in standard microscopic calculations and that the low energy part of the spectrum can thus be described. As an application, we will discuss the contribution of these collective modes to the specific heat in comparison with other known contributions.

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Time-dependent simulations of force-free magnetospheres

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We present preliminary results from a new force-free electrodynamics code that simulates time-dependent neutron star magnetospheres. Our pseudospectral code uses global Fourier and Chebyshev expansions to take spatial derivatives, resulting in very low dissipation and dispersion error, and can accurately evolve sharp field discontinuities (current sheets). As a first test, we calculated the onset of the electromagnetic wind from an axisymmetric pulsar. We then studied the twisted closed magnetospheres of magnetars: they can over-twist, open, and close again, a cycle which is seen in our simulations. The code can also be used to analyse the development of Alfvenic turbulence in the magnetosphere following a starquake.

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A Mildly Recycled Accreting X-ray Pulsar in the Globular Cluster Terzan 5

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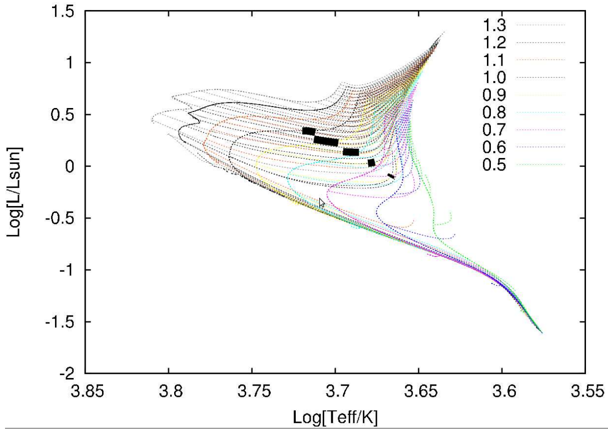

Figure 1: Evolutionary tracks of donor stars with mass between 0.5 and 1.3 $M_{\odot}$. The stars experience Roche lobe overflow during their evolution in a binary with a 1.4 $M_{\odot}$ neutron star. All donors that match the observed parameters of the 11 Hz pulsar in Terzan 5 are on the sub-giant branch and are indicated with a thick black segment

Accreting Millisecond X-ray Pulsars (AMXPs) provide the evolutionary link between the young slowly rotating and strongly magnetized pulsars and the old rapidly rotating and weakly magnetized millisecond pulsars. In October 2010 a new accreting pulsar (named IGR J17480-2446) has been discovered in the globular cluster Terzan 5 [1], whose spin frequency of 11 Hz was surprisingly low for an old neutron star in a low mass X-ray binary. Detailed timing analysis of the pulsar indicate that it is in its spin up evolutionary phase. The anomalous long spin period however can be explained with two possible scenarios: an exceptionally early phase of the spin-up epoch, or the proximity to the spin equilibrium due to an unusually strong pulsar magnetic field (when compared to typical fields in AMXPs). We present here a detailed periodic timing study and discuss implications for the accretion torque history of this enigmatic pulsar. Thanks to combined results from timing observations, globular cluster photometry and binary evolutionary models, it is possible to set precise constraints on the evolution of the pulsar and its companion star (see Figure 1). The results of this study have strong implications for our knowledge of pulsar evolution and accretion torque modeling in low mass X-ray binaries.

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Recent NIR-optical-UV observations of pulsars

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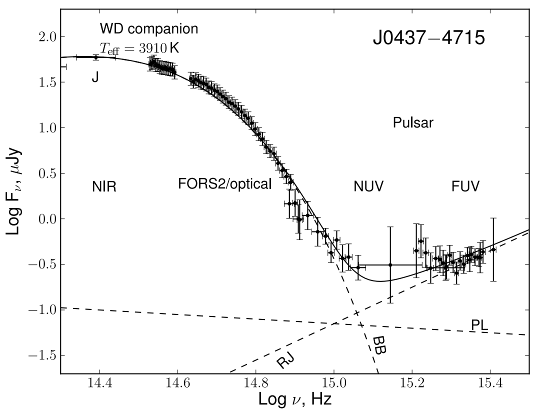

Figure 1: NIR-optical-UV spectrum of the binary millisecond pulsar J0437–4715 (from Ref. [2]). The spectrum is dominated by the cold white dwarf companion at $\lambda > 3000$ Å ($\log \nu < 15.0$), while the thermal pulsar's spectrum dominates in FUV.

NIR-optical-UV observations of neutrons stars, including rotation-powered pulsars, are very important for understanding the thermal emission from the neutron star surface and nonthermal (apparently synchrotron) emission from their magnetospheres. However, because of their extreme faintness, only about 10 pulsars have been detected in this wavelength range since the discovery of the optical pulsations of the Crab pulsar in 1969 [1]. Despite the small amount of the NIR-optical-UV data on pulsars (most of them from the *Hubble Space Telescope*), their study has made a significant contributution to our understanding of neutron star physics. We will present a brief overview of the results of NIR-optical-UV observations of pulsars and their connection with the X-ray and γ-ray data, with emphasis on our own recent results. Among others, we will report on multi-wavelength observations of the nearest millisecond pulsar J0437–4715 (so far the only recycled pulsar detected in this range) and its cold white dwarf companion (see Fig. 1), as well as the multi-wavelength spectrum and pulsations of the middle-age PSR B0656–14.

This work was partially supported by NASA (grant NNX09AC84G) and by the Ministry of Education and Science of the Russian Federation (contract 11.G34.31.0001).

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Constraining the mass and moment of inertia of neutron stars from quasi-periodic oscillations in X-ray binaries

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Neutron stars are the densest objects known in the Universe. Their internal composition and structure are rather poorly constrained by measurements. We will show how to put some constraints on the mass and moment of inertia of neutron stars based on the interpretation of kHz quasi-periodic oscillations observed in low mass X-ray binaries (LMXBs).

We use observations of high-frequency quasi-periodic oscillations (HF-QPOs) in LMXBs to look for the average mass and moment of inertia of neutron stars. This is done by applying our parametric resonance model (see Ref.[1] and references therein) to discriminate between slow and fast rotators. We fit our model to data from ten LMXBs for which HF-QPOs have been seen and the spin of the enclosed accreting neutron star is known.

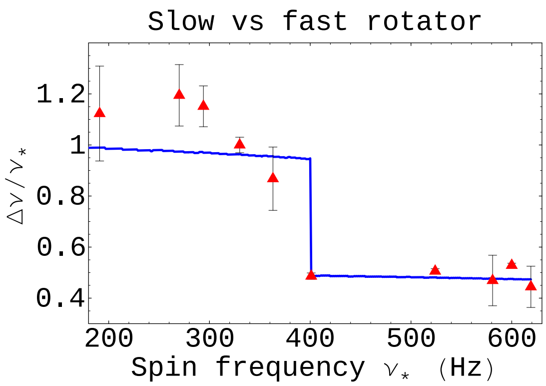

Figure 1: The dichotomy between slow and fast rotators constrains the average mass of neutron star (from Ref.[2]).

For our simplified analysis we assume that all neutron stars possess the same properties (same mass M_* and same moment of inertia I_*). We find an average mass $M_* \approx 2.0$–$2.2\,M_\odot$. The respective average moment of inertia is then $I_* \approx 1-3\times 10^{38}\,\mathrm{kg\,m^2} \approx 0.5-1.5\,(10\ \mathrm{km})^2\,M_\odot$ which corresponds to dimensionless spin parameter $\tilde{a} \approx 0.05-0.15$ for slow rotators (neutron stars with the spin frequency roughly about 400 Hz, Ref.[3]) and $\tilde{a} \approx 0.1-0.3$ for fast rotators (neutron stars with the spin frequency roughly about 600 Hz), Ref.[2], see Fig. 1.

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A unified polar cap/striped wind model for pulsed radio and gamma-ray emission in pulsars

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Since the discovery by the Fermi/LAT instrument of more than fifty new gamma-ray pulsars, it becomes possible to look for statistical properties of their pulsed high-energy emission, especially their light-curves and phase-resolved spectra, Ref.[1]. These pulsars emit mostly gamma-ray photons but some of them are also detected in the radio band. For the latter, the relation between time lag of radio/gamma-ray pulses and gamma-ray peak separation, in case both high-energy pulses are seen, helps constrain the magnetospheric emission mechanisms and location.

I will show how to relate radio and gamma-ray pulses, assuming a polar cap model for the former and the striped wind geometry for the latter. It is an extension of previous synchrotron and inverse Compton emission models, Ref.[2, 3]. I will show radio and gamma-ray light-curves, summarizing the results in several phase plots. The phase lag as well as the gamma-ray peak separation dependence on the pulsar inclination angle and on the viewing angle are studied, Ref.[4]. I predict the radio lag/peak separation relation for comparison with the Fermi catalog, Fig. 1.

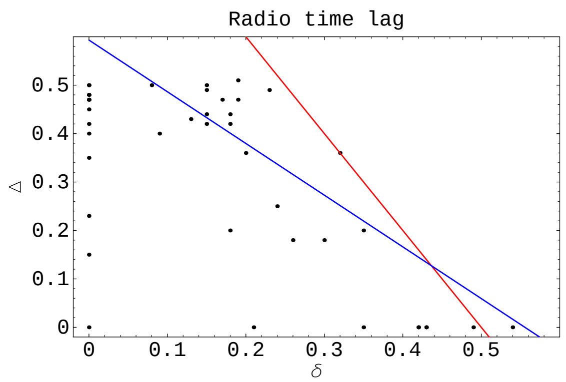

Figure 1: Predicted (red curve) and observed (blue curve) relations for the radio/gamma-ray time lag (from Ref.[4]).

This simple geometric model explains the observed radio/gamma-ray correlation satisfactorily. This supports the idea of distinct emission locations for the radio and gamma-ray radiation. Nevertheless, time retardation effects like curved-space time and magnetic field lines winding up close to the neutron star can lead to discrepancy between our predicted time lag and a more realistic relation as deduced from the gamma-ray catalog.

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First dedicated X-ray and optical observations of the isolated neutron star in the Carina Nebula

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2XMM J104608.7-594306 is a newly discovered isolated neutron star (INS) sharing most of the properties of the intriguing "Magnificent Seven" (M7). In spite of many efforts (e.g. [1, 2]), this is the first example of a thermally emitting INS to be detected beyond the Gould Belt [3, 4]. The neutron star displays a purely thermal soft X-ray emission, stable flux, has no counterparts at other wavelengths and is likely located in the Carina Nebula, roughly at a distance of 2 kpc. 2XMM J104608.7-594306 is unique since it has an intermediate temperature between the M7 and the only rotating radio transient (RRAT) thus far detected in X-rays. Current estimates on the birthrates of thermally emitting INSs and RRATs show that they may greatly outnumber active radio pulsars. In this case, the rate of Galactic core-collapse supernovae cannot account for all different observational manifestations of INSs without invoking relations between the several subgroups. The investigation of the properties of this INS is therefore of particular importance since it may well be a missing link between the M7, magnetars and RRATs. We report here the results of a dedicated observational campaign with XMM-Newton and the VLT on 2XMM J104608.7-594306, which are used to constrain its evolutionary status and to shed light on its relation to other INSs.

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Evolution and observational appearance of isolated neutron stars with decaying magnetic fields

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We study evolution of isolated neutron stars using the population synthesis technique [1] in the framework of decaying magnetic field. We use the model of field decay developed in [2]. At first we perform population synthesis of different populations of young isolated neutron stars (radio pulsars, close-by cooling neutron stars, magnetars) to derive the initial field distribution which can explain all neutron star types under study in the same framework. Then we apply this model to study the evolution of neutron stars on long time scale.

The initial field distribution which successfully explains the main properties of young isolated neutron stars (except central compact objects) is log-gaussian with $\sigma = 0.6$ and $< \log B_0/[G] >= 13.25$ [3]. These parameters are not very sensitive to the model parameters, but they can vary a little in different sets.

Using this initial field distribution and the decay law from [2] (in this approach field decay after few million years is negligible, strong rapid decay happens only for initially large field values) we model the population of old neutron stars to study properties of accreting isolated compact objects. We find that due to initially high fields a significant fraction of isolated neutron stars reaches the stage of accretion [4]. Objects similar to the Magnificent seven are the main progenitors of accreting isolated neutron stars.

In addition, we discuss new results related to the distribution of close-by cooling neutron stars in the $P - \dot{P}$ plane, and comment on the population of central compact objects which appears to be a separate group of objects with different initial distributions.

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X-ray observations of old radio pulsars and the example of PSR B1451–68

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Very few old radio pulsars are detected in X-rays. These objects are in general very faint due to their cold surfaces and relatively low spin-down powers. Yet, old radio pulsars appear to convert their spin-down energy more efficiently into X-ray emission than their younger relatives. It is unclear how much of this X-ray emission can be attributed to thermally emitting, hot polar caps or to magnetospheric emission. The evolution of NS magnetospheres with age and the polar cap heating mechanism are both interesting for the entire NS population, but can be particularly well studied in the case of old X-ray detected radio pulsars. We will present a summary of the current observational constraints on the high-energy emission of old pulsars. As an example, we will also present recent Chandra observations of the 4.25×10^7 yrs old radio pulsar PSR B1451–68. The spectrum of the found X-ray source can be described by a power law with photon index ~ 2.7. Its isotropic luminosity is $L_X \sim 1.7 \times 10^{30} d^2{}_{450pc}$ erg/s (0.3 keV to 8keV), which corresponds to a high X-ray efficiency of 8×10^{-3}.

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Maximally model independent equation of state for neutron star matter

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We develop a theoretical approach to reconstruct equation of state (EOS) by Bayesian analysis that can incorporate the inherent observational errors in the data of individual neutron stars. If the errors are large, the reconstructed EOS would lie in a band in the pressure-energy density plane. With more observed stars, more detailed knowledge of their properties and progressively smaller errors, a unique curve could be obtained. Instead of pressure as a function of density, we take advantage of using the squared adiabatic speed of sound in our analysis.

EOS was already inferred in the recent article [1], where data from X-ray bursts were used. The EOS was parameterized by considering microscopic physics of nuclear matter and recovered by Markov chain Monte Carlo algorithm within the Bayesian framework. Our scheme differs mainly by a more general approach, where we generate piecewise EOS based on fundamental physical assumptions: causality, stability and relative 'smoothness' of EOS. It minimizes the model dependence and allows one to study various physical hypotheses (phase transitions, $f(R)$ gravity). Sequential Bayesian analysis statistically weighs EOS, can easily incorporate additional data and constraints, as well as use different observables of a compact object (Love number, binding energy).

We apply the algorithm to the same X-ray data [1] and produce consistent results in the form of the statistically weighted EOS band.

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X-ray pulsars

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Present observations and theoretical understanding of accreting neutron stars with strong magnetic fields in binary systems (X-ray pulsars) will be discussed. Long-term and short-term variability (outbursts) of the sources and the spin-up/spin-down histories of disk and wind-fed X-ray pulsars will be discussed in more detail. A hydrodynamic theory of quasi-spherical wind accretion onto slowly rotating neutron stars without accretion disks are discussed [1]. In this model, at X-ray luminosities below some critical value about 3×10^{36} erg/s, the accreting matter subsonically settles down onto the rotating magnetosphere forming an extended quasi-static shell. During spin-up/spin-down episodes, this shell mediates the angular momentum transfer to/from the rotating neutron star magnetosphere by large-scale convective motions. The accretion rate through the shell is determined by the ability of the plasma to enter the magnetosphere. Angular momentum distribution in the shell is calculated depending on the degree of anisotropy of turbulence in the shell, and the corresponding equilibrium spin periods of neutron stars are found. The Bondi accretion problem is solved taking into account turbulent heating and Compton cooling of the gas. The model enables one to estimate the magnetic field of X-ray pulsars from observations of their spin-up/spin-down rates and X-ray luminosities. The model explains both the quasi-regular saw-tooth behavior of the pulsar frequency on large time-scales observed in some pulsars where quasi-spherical settling accretion can be realized (GX 1+4, Vela X-1, GX 301-2) and the irregular short-term frequency fluctuations, which can correlate or anti-correlate with the X-ray flux fluctuations in different systems.

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Theory of thermal radiation from isolated neutron stars

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The theory of formation of thermal spectra of isolated neutron stars is reviewed with emphasis on the case where a strong magnetic field exists at the stellar surface. Characteristic spectral features and their dependences on stellar parameters are considered. It is shown how the physics of dense, strongly magnetized plasmas manifests itself in the thermal radiation of isolated neutron stars. Topical problems related to interpretation of modern observations of such thermal radiation are discussed.

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New advances in spectral modeling of X-ray bursts and constraints on neutron star parameters

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X-ray bursts are a powerful tool to determine neutron star masses and radii, if the Eddington flux and the apparent radius in the cooling tail can be measured accurately, and distances to the sources are known. We discuss here an improved method of determining stellar parameters using the data from the whole cooling phase of photospheric radius expansion bursts.

We first computed a large set of model atmospheres and emergent spectra covering a range of luminosities for different chemical compositions and surface gravities. The emergent spectra of all models are redshifted and fitted by a diluted blackbody in the *RXTE*/PCA 3–20 keV energy band, and corresponding values of the color correction f_c are presented (see Ref. [1] for more details).

We then consider observed variations of the apparent blackbody radius with flux in photospheric radius expansion bursts in 4U 1724–307 and 4U 1608–52. We find that spectral evolution of the bursts strongly depends on the persistent flux. The spectra of bursts at high accretion rates contradict the theory significantly being probably strongly affected by the accretion flow. The bursts that happen at low accretion rates show evolution consistent with theory of passively cooling neutron star, and can therefore be used to determine neutron star parameters.

Our method allows us to determine both the Eddington flux and the ratio of the stellar apparent radius to the distance much more reliably. We find a lower limit on the neutron star radius in 4U 1724–307 of 14 km for masses below $2.2M_{\odot}$, independently of the chemical composition. These results suggest that the matter inside neutron stars is characterized by a stiff equation of state. (see Ref. [2] for more details). Our findings for 4U 1608–52 are consistent with the results on 4U 1724–307.

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Model of extended emission of short Gamma-ray Bursts

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Till now the extended emission is an intriguing property of short duration bursts. It is not clear what the nature of the extended emission is. It might be rising x-ray afterglow or it could be manifestation of prolonged activity of a central engine.

We consider short gamma-ray bursts emphasizing common properties of short bursts and short bursts with extended emission. Assuming that the extended emission with broad dynamic range is a common property of short bursts we propose a two jet model which can describe both short main episode of hard emission, specific for short bursts, and softer extended emission by different off axis position of the observer. The toy model involves a short duration jet powered by heating due to $\nu\tilde{\nu}$ annihilation and long-living Blandford-Znajek jet with significantly more narrow opening angle.

Proposed model is a plausible mechanism of short duration burst energization and can explain short bursts with and without extended emission within a single class of progenitors.

Comparative analysis of GX 339-4 and Aql X-1 outbursts

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We present the comparative analysis of the black hole X-ray transient GX 339-4 and the neutron star transient Aql X-1 in their most intriguing hard state. Both sources demonstrate quasi-regular X-ray outbursts allowing one the direct exploration of the dynamics and characteristics of non-stationary accretion in such systems.

Our analysis aims to identify common and different features of accretion onto such objects and their X-ray spectrum formation, which could help propose methods of the compact object identification in such transients.

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Annular gap model for high-energy emission from normal and millisecond pulsars

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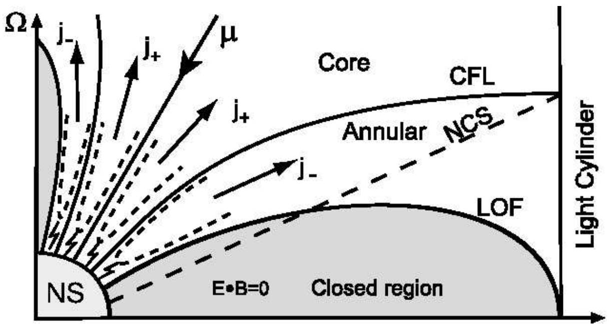

Figure 1: A schematic diagram for the annular and the core regions for an inclined rotator (Qiao et al. 2007). The null change surface (NCS) is the surface where $\Omega \cdot B = 0$. Line 'CFL' and 'LOF' are the critical field line and the "last" open field line respectively. The upper boundaries of the pair formation front are denoted by dashed lines.

The radiation mechanism of pulsars is still an open question. It will be shown that the annular gap could be formed in the magnetosphere of neutron stars or quark stars, which presents the advantages of the polar cap/slot gap and outer gap models. Here some related observational and theoretical affairs are discussed: (1) Radio emission models are compared with observations; (2) Gamma-ray emission models are reviewed and compared with observations. In the annular gap model, the potential drops in the annular region can be high enough to produce gamma-rays for young pulsars and millisecond pulsars which have been observed by the Fermi-LAT. Based on the annular gap model both radio and gamma-ray emission can be simulated (Du et al. 2011); (3) Radiation formation locations of high energy emission can be determined from observations (see Lee et al. 2010); (4) Possible sub-millisecond pulsar formation process and its observable properties are discussed (Du et al. 2009). It is emphasized that a discovery of a sub-millisecond pulsar would be very important for distinguishing neutron stars from quark stars.

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Weak Decay Rates and Mechanism of Supernova Explosions

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Weak decay rates play a preeminent role in the collapse of stellar core in the stages leading to a Type-II supernova. Weak decay rates from ground and excited states are calculated for the core-collapse supernova dynamics and for probing the concomitant nucleosynthesis problem. The stellar weak rates are sensitive to the location and structure of low-lying states in daughter ^{57}Cu. The structure of ^{57}Cu plays a crucial role in the nucleosynthesis of proton-rich nuclei. The primary mechanism for producing such nuclei is the rp-process and it is believed to be important in the dynamics of the collapsing supermassive stars. Small changes in the binding and excitation energies can lead to significant modifications of the predictions for the synthesis of proton rich isotopes. The β^+-decay and electron capture (EC) rates on ^{57}Zn are compared to the seminal work of Fuller, Fowler and Newman (FFN). The pn-QRPA calculated β^+-decay rates are generally in good agreement with the FFN calculation. However at high stellar temperatures the calculated β^+-decay rates are almost half of FFN rates. On the other hand, for rp-process conditions, the calculated EC (β^+-decay) rates are bigger than FFN rates by more than a factor 2 (1.5) which may have interesting astrophysical consequences.

Observations of neutron stars in low-mass X-ray binaries

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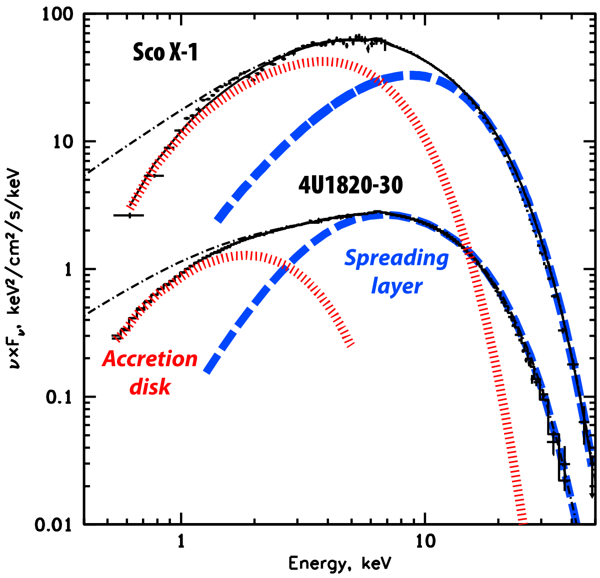

Figure 1: General decomposition of X-ray emission of low mass X-ray binaries with neutron stars. Contributions of accretion disk and the boundary/spreading layer are labeled.

Low mass X-ray binaries with neutron stars (NS LMXBs) have two main regions, where the gravitational energy of the accreting matter is converted into heat and radiation. These are accretion disk and the boundary layer between the accretion disk and the neutron star surface, where the accreting matter is settling to the NS rotational velocity. In spite of the fact that overall contribution of the boundary layer is comparable to that of the accretion disk, it is astonishingly complicated to measure its energy spectrum in a model independent way. I will demonstrate that it is possible to do making use of the so-called Fourier frequency resolved spectral analysis and will show important consequences of these measurements. In particular, I will show 1) that accurate measurements of the spectra of boundary layer allow us to constrain masses and radii of accreting neutron stars, 2) that the entire fast variability, observed in NS LMXBs physically originates in the boundary layer, thus providing limitations for all theories of fast quasi-periodic oscillations, 3) that simple toy model of the evolution of the inner part of the accretion flow allows us to provide reasonable explanation of the observed puzzling "Z-like" or "atoll-like" behavior of luminous NS LMXBs.

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Modeling of Accreting Millisecond Pulsars

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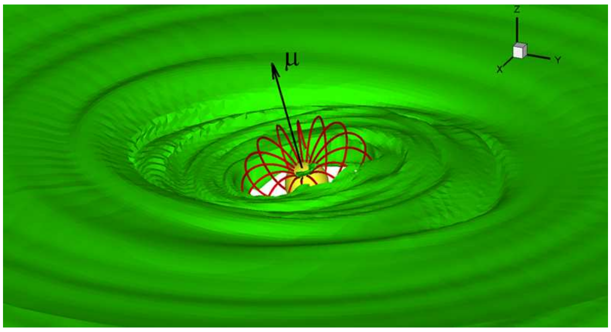

Figure 1: Example of 3D MHD simulations of warp formation around millisecond pulsar.

Accreting millisecond pulsars are weakly magnetized neutron stars accreting from a disk and radiating in the X-ray band. Some of them show periodic oscillations, but the majority show only quasi-periodic oscillations including a pair of drifting kHz oscillations, and also lower frequency oscillations. We model millisecond pulsars as rotating stars with tilted dipole field and perform global 3D MHD simulations of disk accretion onto such stars using our 'cubed sphere' code [1] and a pseudo-Newtonian potential to model general relativistic effects [2]. Simulations show that the accreting matter is lifted above the magnetosphere in two ordered funnel streams, or that it accretes directly in the equatorial plane in less ordered 'tongues' [3]*. In both cases, the hot spots where the streams hit the star rotate faster or slower than the star and can be responsible for one or two frequencies [4, 5]. On the other hand, the tilted magnetosphere excites waves in the disk which can also be responsible for oscillations at different frequencies. The most prominent feature is the one-armed warp which rotates with the frequency of the star, or at lower frequencies (see Fig. 1). We often see that the main frequencies connected with moving spots are associated with the frequency of waves excited in the inner disk.

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Resonant axion production in magnetar magnetosphere

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The scattering of the surface thermal X-ray photons off ultrarelativistic electrons with axion production, $\gamma + e \to e + a$, in the vicinity of magnetar polar cap was considered. The amplitude of the axion production process was calculated in the limit, where the initial electron is on the ground Landau level but final and virtual electrons occupy arbitrary Landau levels. It has been shown that the cyclotron resonances are responsible for the main contribution to the amplitude. The number of axions produced by the X-ray radiation in the magnetar magnetosphere has been determined. The possible astrophysical consequences of the resonant processes are discussed.

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The 2009 outburst of magnetar 1E 1547−5408: Persistent radiative and burst properties

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The magnetar 1E 1547−5408 recently exhibited two periods of outburst, beginning on 2008 October 3 and 2009 January 22. Here we present an analysis of the persistent radiative evolution and a statistical study of the burst properties during the 2009 outburst using the *Swift* X-ray Telescope (XRT). We find that the 1–10 keV flux increased by a factor of ~ 500 and hardened significantly at the onset of the outburst. The pulsed fraction decreased to zero at the peak of the outburst, exhibiting an anti-correlation with phase-averaged flux. Properties of the several hundred X-ray bursts during the 2009 outburst were determined and compared to those from other magnetar outburst events. We find that the peaks of the bursts occur randomly in phase but that the folded counts that compose the bursts exhibit a pulse which is misaligned with the persistent pulse phase. We compare the hardness-flux evolution of the persistent emission of both outbursts to those from other magnetars and find that although there does exist an overall trend, the degree of hardening for a given increase in flux is not uniform from source to source. These results are discussed in the context of previous results and within the magnetar model.

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New identification of young Crab-like pulsars in the optical and infrared

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We report on new optical and IR identifications of several young energetic pulsars with Crab-like pulsar wind nebulae around them best visible in soft X-rays. Most intriguing feature of the identifications is a strong mid-IR excess in the emission of the pulsars and their nebulae as compared to the optical range. This is in contrast to the Crab, where the excess is absent. We discuss possible interpretations of the excess and further observations to be performed for understanding its nature.

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Cooling neutron star in the Cassiopeia A supernova remnant: Evidence for superfluidity in the core

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According to recent results of Ho and Heinke [1, 2], the Cassiopeia A supernova remnant contains a young neutron star which has carbon atmosphere and shows noticeable decline of the effective surface temperature. The additional (November 2010) Chandra observation shows that the decline continues at the same rate [4]. The observed decline is naturally explained if triplet-state neutron superfluidity appeared recently in the neutron star core, producing a splash of neutrino emission due to Cooper pair breaking (CPB) process that currently accelerates the cooling [3, 4]. This scenario puts stringent constraints on poorly known properties of neutron star cores: on density dependence of the temperature $T_{cn}(\rho)$ for neutron superfluidity onset (should be a wide peak with maximum $\approx (5-9) \times 10^8$ K), on the reduction q of CPB process by collective effects in superfluid matter ($q \gtrsim 0.4$), and on the neutrino emission before neutron superfluidity onset (30–100 times weaker than the modified Urca). This is serious evidence for nucleon superfluidity in neutron star cores that comes from observations of cooling neutron stars.

This work was supported by the Russian Foundation for Basic Research (grant 11-02-00253, 11-02-12082-ofim-2011), Rosnauka (grant NSh 3769.2010.2), Ministry of Science and Education of Russia (contract 11.G34.31.0001), Science and Technology Facilities Council (STFC) in the United Kingdom (grant PP/E001025/1), Dynasty Foundation, RF Presidential Program (grant MK-5857.2010.2), and the Natural Sciences and Engineering Research Council (NSERC) of Canada.

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Decomposition of polarization components of the Crab pulsar and its nebula

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We compare archival polarization HST/ACS data on the Crab nebula with the polarization characteristics obtained using the very fast photo-polarimeter Optical Pulsar Timing Analyzer (OPTIMA). Our highly time resolved OPTIMA observations allow us to decompose the polarized radiation into components of the pulsar, a localized DC source, and the surrounding nebula. By cross correlation with the spatial polarization map from HST we can investigate the origin of the DC emission. The orientation of the phase-averaged position angle of the Crab pulsar is compared with its axis of rotation and the symmetry axis of the X-ray torus surrounding the pulsar. Moreover, in the context of the phase-averaged polarization degree and position angle, the Crab pulsar results are compared with the results for two next brightest pulsars, PSR B0540–69 and the Vela pulsar (PSR B0833–45).

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Pulse intensity distribution of pulsar B0950+08

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Observations of individual pulses of pulsar B0950+08 at frequency 112 MHz were carried out using the BSA telescope of Pushchino Radioastronomy Observatory of FIAN. We detected very strong pulses exceeding the amplitude of the mean profile by more than one hundred times. The mean profile has 3 components. At the phase of the leading component we have rare but very strong pulses exceeding the amplitude of the mean profile at this phase by more than 400 times. We have analyzed cumulative probability distribution of pulse intensities for all observed pulses with signal to noise ratio greater than 5 (3385 pulses) and have shown that the distribution is described by a piece-wise power-law with a slope changing from $n = -1.25 \pm 0.04$ to $n = -1.84 \pm 0.07$ for intensities greater than 600 Jy. Thus we conclude that we have detected giant pulses from this pulsar having the same signature as giant pulses of other pulsars. We present also phase analysis of individual pulse behavior.

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Formation of "lightnings" in an RRAT magnetosphere

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Rotating radio transients (RRATs) are neutron stars characterized by sparse, short, relatively bright, dispersed bursts of radio emission. Their discovery was reported in 2006. The typical burst rate lies in the range of 1 min^{-1} to 1 h^{-1}. We consider a possible link between "lightnings" in a neutron star magnetosphere and radio bursts from RRATs. Such "lightnings" are initiated by absorption of diffuse gamma-ray emission in the inner magnetosphere and subsequent generation of a secondary electron-positron plasma. The length of the "lightning" reaches 1000 km, its radius equals 100 m and is comparable with the polar cap radius. The necessary condition for the "lightning" formation is the existence of a strong electric field close to the vacuum field. If the closed magnetosphere is filled with a dense plasma, the formation of "lightnings" is efficient only in the region of open magnetic field lines. In a weak magnetic field, synchrotron photons make a major contribution to pair creation. High pair creation rate leads to the dynamic screening of the electric field, which is produced by progressive increase of the electric current in the "lightning", and not by charge separation. High density and multiplicity of the generated plasma allow us to assume that we can observe radio emission from the "lightnings" in the form of short single radio bursts. Their characteristics are similar to those of the RRAT bursts. In order to observe radio emission from a separate "lightning", the polar cap of the neutron star must be directed towards the observer and the "lightning" must form simultaneously. The burst rate is proportional to the gamma-ray photon absorption rate in the region of open magnetic field lines. Were the gamma-ray background too intensive, RRATs could not exist. The maximum surface magnetic field which allows the neutron star to be an RRAT is $\sim (1-4)\times 10^{14}$ G. The maximum burst rate is related to the time of the plasma outflow from the polar cap region. The typical interval between two consecutive bursts is ~ 100 s. The width of a single radio burst can be determined either by the width of the emission cone formed by emitting areas of the "lightning" at a particular height over the neutron star surface or by a finite lifetime of the "lightning". The width of the phase distribution of radio bursts from an RRAT, along with the integrated pulse width, is determined by the width of the bundle of open magnetic field lines at the height where radio emission forms. The obtained results are consistent with contemporary observational data and indicative of the close link between RRATs, intermittent pulsars and extreme nullers.

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Magnetized neutron star atmospheres: beyond the cold plasma approximation

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Harmonically spaced absorption features are observed in thermal soft X-ray spectra of some isolated neutron stars [1, 2]. The interpretation of the features as quantum resonances of magnetic free-free opacity has been recently suggested, and respective neutron star atmosphere models have been calculated in the cold plasma approximation [3]. This approximation neglects the cyclotron emission of electrons at the harmonics of the cyclotron frequency, as well as the Doppler broadening of the cyclotron resonances, which may be important even at the relatively low temperatures of neutron star atmospheres. To demonstrate this effect, we calculate models of hydrogen neutron star atmospheres with $B \sim 10^{10}$–10^{11} G (i.e., the electron cyclotron energy $E_{c,e} \sim 0.1$–1 keV) and $T_{\rm eff} = 1$–3 MK with the thermal cyclotron opacities [4] taken into account. Such conditions are thought to be typical for the so-called central compact objects in supernova remnants, such as 1E 1207.4–5209 in PKS 1209–51/52. We show that the "warm plasma effects" are very significant in first three cyclotron harmonics, and they should be taken into account for the proper interpretation of the observed spectra, in addition to the quantum oscillations in the magnetic free-free opacity.

This work was supported in part by the Ministry of Education and Science of the Russian Federation (contract 11.G34.31.0001).

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Proton localization and magnetic field evolution in dense neutron star matter

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The realistic models of neutron star matter share the property that the nuclear symmetry energy saturates and decreases at high densities. This implies a low proton fraction in the nuclear matter. At high densities the protons behave as polarons which are localized [1]. Localized protons induce a ferromagnetic instability in the form of spin ordering. The spin-ordered phase in the core of a neutron star generates a strong magnetic field. The density-dependent effective proton magnetic moment and magnetization change sign at some density. We discuss here the model of ferromagnetic origin of magnetic fields of neutron stars. The magnetic phase transition occurs soon after formation of the neutron star but at the beginning the core magnetic field is fully screened. The emergence of the magnetic field takes a long time because of the high electrical conductivity of the magnetic core [2]. We compare our results with measured neutron star masses and their magnetic fields.

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Study of Young Pulsar Wind Nebulae and Their Pulsars with a Spectral Evolution Model

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We study two young pulsar wind nebulae (PWNe) which have only upper limits on γ-ray flux, 3C58 and G310.6-1.6, using the spectral evolution model of PWNe developed for and applied to five PWNe observed in TeV γ-rays (TeV PWN), the Crab Nebula, G21.5-0.9, G54.1+0.3, Kes 75 and G0.9+0.1, in our previous works [1, 2]. We model the evolution of the magnetic field and the particle distribution function inside a uniformly expanding PWN considering time-dependent injection from the pulsar and radiative and adiabatic losses.

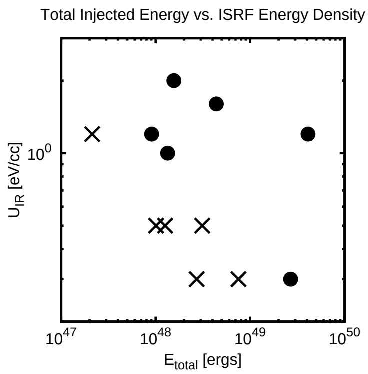

Figure 1: Total injected energy and the adopted ISRF energy density for each PWN are plotted. These include young PWNe which have only flux upper limits in γ-rays (cross) and which are observed in TeV γ-rays (circle).

The flux upper limit in γ-rays gives the lower limit of the expansion velocity and the ratio of the magnetic field energy inside the PWNe to the total energy injected from their central pulsar, $\gtrsim$ 800km/s and $\gtrsim 3\times10^{-3}$ for 3C58 and $\gtrsim$ 2000km/s and $\gtrsim$ a few $\times10^{-4}$ for G310.6-1.6, respectively. These results enhance our conclusion on previous work [2], which young TeV PWNe have the expansion velocity $\sim$ 1000 – 2000km/s and the fraction of the magnetic energy $\sim$ a few $\times10^{-3}$. Figure 1 plots the total injected energy and the adopted ISRF energy density for each PWN applied our model. We should note that the fraction of the magnetic energy $\sim$ a few $\times10^{-3}$ is assumed for PWNe which have flux upper limit in γ-rays. We find TeV PWNe have the large total injected energy and (or) the large ISRF energy density. The other correlations between the observability of PWNe in γ-rays and the age of PWN, the distance to PWN or the spin-down luminosity of the central pulsar are not found.

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Nonequilibrium layer of neutron stars

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The matter in the neutron star crust should have a nuclear composition, which may be far from the equilibrium one. This composition depends on the way of the formation of the neutron star. In the case of the formation of a hot NS during collapse and SN explosion very heavy nuclei are formed in the outer crust, very overabundant by neutrons.

Properties of this non-equilibrium layer are calculated by solving Oppenheimer-Volkov equation of star equilibrium. We find values of thickness, mass and energy storage of the non-equilibrium layer as a function of the neutron star mass. It is shown, that the thickness, the mass of the non-equilibrium layer, and its energy storage are increasing with decrease of the NS mass, and for $M_{ns} = 0.5M_{\odot}$ the mass of the non-equilibrium layer is about 10 times larger, than for the star with $M_{ns} = 1.4M_{\odot}$.

The fission reaction in the matter of this layer after its transfer to lower densities during a starquake may be related to the SGR activity. The best candidates for it are low mass neutron stars, where the energy of the nuclear explosion has a maximum.

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New data on profiles and dynamic spectra of two XDINSs at low frequencies

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XDINSs (X-ray dim isolated neutron stars) are a small group of near and young neutron stars discovered by ROSAT and characterized by purely thermal spectra ($kT \sim 40 - 100$ eV), and long spin periods ($P \sim 3 - 11$ s). The presence of the absorption feature in the X-ray spectra of a few XDINSs give the possibility to measure the magnetic field strength independently of the spin-down measurements. In the $P - \dot{P}$ diagram XDINSs, like RRATs (rotating radio transients), are placed between normal pulsars and magnetars. We present the new data of radio observations of two XDINS (1RXS J2143.7+065419 and 1RXS J130848.6+212708) at low frequencies. The observations were carried out on two sensitive transit radio telescopes at a few frequencies in the range 42-112 MHz. The flux densities and mean pulse profiles as well as the estimation of the dispersion measures, distances and integrated radio luminosities of both objects are presented. Pulse profiles and dynamic spectra have been obtained with the aid of new digital receivers. Results of the correlation analysis of data, allowing one to determine the dispersion measure by an independent method, are given as well. Comparison with X-ray data shows large differences in the mean pulse widths and luminosities.

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Bondi-Hoyle Accretion onto Magnetized Neutron Star

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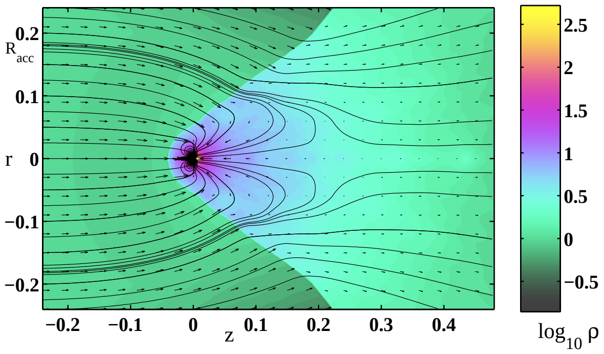

Figure 1: Matter flow around a weakly magnetized star propagating through the interstellar medium with Mach number $\mathcal{M} = 3$.

We use axisymmetric magnetohydrodynamic simulations to investigate the Bondi-Hoyle accretion onto a neutron star with a dipole magnetic field and interaction of supersonic neutron star with the ISM.

A non-magnetized star moving through the ISM captures matter gravitationally from the accretion radius R_{acc}, and the mass accretion rate at high Mach numbers was derived by Hoyle and Lyttleton [2]. For arbitrary Mach number $\mathcal{M}$ a general formula was proposed by Bondi [1], [3].

If the moving star has a magnetic field, the situation is more complex. The magnetosphere interacts with the incoming ISM flow and the ISM pressure equals to the magnetic pressure of the magnetosphere at a radius R_m. If $R_m > R_{acc}$, then the ISM interacts directly with the star magnetosphere. This case is relevant for example for stars with a high magnetic moment (magnetars) or stars with a very high velocity.

On the other hand, if $R_m < R_{acc}$, the situation is different. First, matter is captured by the gravitational field of the star like in Bondi-Hoyle accretion onto a non-magnetic star. It is accumulated near the star and interacts with the magnetic field of the star. Second, the magnetosphere of the star acts as an obstacle for the flow and a magnetized star accretes matter at a *lower* rate than a non-magnetized star for the same parameters v, c_s, and M.

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The quiescent X–ray emission of AXPs and SGRs – powered by magnetic field decay or by accretion ?

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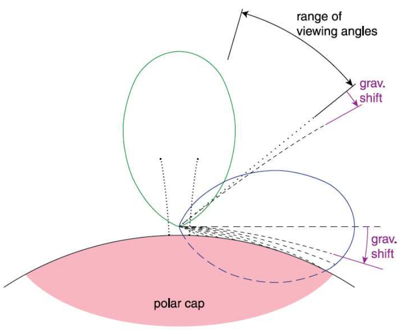

Figure 1: Schematic view of the geometry (from Ref. [4]).

Anomalous X–ray Pulsars (AXPs) and Soft Gamma–ray Repeaters (SGRs) constitute a special class of young neutron stars, which are thought to be magnetars, i.e. neutron stars with superstrong magnetic fields ($> 10^{14}$ G). Undoubtedly, the strong super–Eddington bursts and giant flares must be powered by the decay of superstrong magnetic fields. However, the quiescent X–ray emission having typical luminosities of a few times 10^{35} erg s^{-1} may be produced by the accretion of matter from a fall–back disk, that has been formed in the supernova explosion [1, 2]. In this model the required dipole field strengths are normal ($10^{12} - 10^{13}$ G), while the sources of bursts and giant flares are located in localized superstrong multipole fields and triggered by crustal shifts. Thus the situation resembles that of the sun which has a weak dipole field and sunspot fields which are stronger by about two orders of magnitude.

This accretion scenario is supported by the recent discovery of an AXP having a modest magnetic dipole field ($< 7 \cdot 10^{12}$ G, [3]). Further evidence is provided by a model explaining the detailed spectral characteristics and energy dependent pulse profiles of the AXP 4U 0142 + 61 [4]. In this model the wide band X–ray emission ($\sim 0.8 - 150$ keV) is explained by bulk comptonization in the accretion column leading to a fan beam (Fig. 1) which in part is absorbed by the polar cap, while another part is reflected (scattered). Both the scattered component and the thermal emission from the polar cap form the polar beam (Fig. 1). This picture explains why the temperature of the polar cap is much higher than those of other young neutron stars. The spectrum of the polar beam shows a bump at $\sim 60 - 70$ keV which can be explained as being due to cyclotron resonance scattering, requiring a polar magnetic field of $\sim (7 - 8) \cdot 10^{12}$ G.

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The relation of the surface small scale magnetic field to braking indicies and inclination angles of radiopulsars

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Some radiopulsars have anomalous braking index values $n = \Omega\ddot{\Omega}/\dot{\Omega}^2 \sim \pm(10^3\text{–}10^4)$. It is shown that such anomalous values may be related to non-dipole magnetic field if the neutron stars of radiopulsars are able to precess [1]. The precession of a neutron star leads to rotation (in the reference frame of the star) of its angular velocity $\vec{\Omega}$ around the direction of the neutron star magnetic dipole $\vec{m}$ with an angular velocity $\vec{\Omega}_p$. This process may cause altering of electric current flowing through the inner gap and consequently the current losses on the time scale of precession period $T_p = 2\pi/\Omega_p$. It occurs because the electric current in the inner gap is determined by the Goldreich-Julian charge density $\rho_{GJ} = -\vec{\Omega}\cdot\vec{B}/(2\pi c)$, which depends on the angle between the direction of a small scale magnetic field and the angular velocity $\vec{\Omega}$.

Taking into account the surface small scale magnetic field and using the model of neutron star rotation from [2] we also investigate the evolution of the inclination angle χ of radiopulsars. We consider two extreme cases of the coupling between the neutron superfluid and the charged components of the star. In the case of the strong coupling the star rotates like a rigid body and, consequently, the inclination angle χ changes slowly and does not achieve the equilibrum value χ_{eq} during the radiopulsar lifetime. In the opposite case of the weak coupling the inclination angle quickly becomes almost equal to the equilibrum value χ_{eq}. Later on, its value changes only due to the precession damping on time scales comparable to the pulsar lifetime. Thus in this case the inclination angles of radiopulsars are mainly determined by the strength of the surface small scale magnetic field.

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Is SGR 0418+5729 a waning magnetar?

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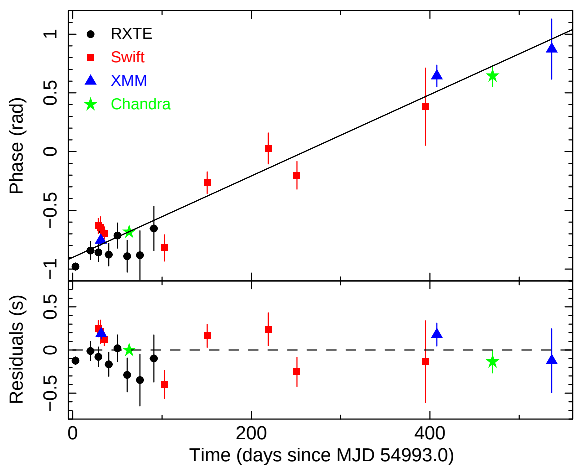

Figure 1: Updated (February 2011) phase-coherent timing solution of SGR 0418+5729.

The recent discovery of a low-field Soft Gamma Repeater, SGR 0418+5729 [1], challenges the widely accepted belief that SGRs (and the Anomalous X-ray Pulsars) are powered by an ultra-magnetized neutron star, a magnetar, with a surface field in excess of the quantum limit $B_Q \simeq 4.4 \times 10^{13}$ G. SGR 0418+5729 was observed for the first time in June 2009 when it entered an outburst state during which X-ray bursts were detected. Despite an intensive X-ray monitoring, no significant evidence for a period derivative was found. The present upper limit is $\dot{P} \sim 5.5 \times 10^{-15}$ s/s, leading to an inferred magnetic field $B < 7.2 \times 10^{12}$ G.

After reviewing the current observational status of SGR 0418+5729, we discuss its timing and spectral properties in the framework of the "old magnetar" scenario. We show that the present values of the period, period derivative and surface magnetic field are compatible with those of an aging ($\approx 10^6$ yr) magnetar endowed with an initially large ($\approx 10^{16}$ G) toroidal component of the internal field. In such a picture, the occurrence of bursts and the spectrum of the persistent emission can be still accounted for by the "standard" magnetar model if the surface field is above $\sim 10^{12}$ G.

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A leptonic model of the SNR RX 1713.7–3946 nonthermal emission

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We found that the multiwavelength spectral shape of the SNR RX 1713.7–3946 can be explained by a leptonic emission model if we assume that this remnant consists of a number of parts with slightly different conditions of particle acceleration and magnetic field amplification. In this model the maximum energy of accelerated electrons is not a constant parameter for the whole remnant but a function of the position in the shell. We also found an upper limit of the thickness of the layer with amplified magnetic field located near the shock front in the remnant. We discuss the possible application of our model to other synchrotron X-ray remnants using Tycho SNR as an example. In order to explain the observed cross-section profile of boundary X-ray emission we suggest a hypothesis of the disturbed and rippled SNR shock front. This hypothesis can be directly checked with the newer generation of X-ray and radio observatories.

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Quasi-Periodic Oscillations

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I shall discuss recent progress in the study of quasi-periodic oscillations from low magnetic field neutron stars. The prospects for QPO observations with large area X-ray detectors will be addressed.

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Numerical solutions of force-free magnetosphere in neutron stars

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The study of the magnetosphere in magnetars is important to understand the properties of observed spectra. Since the Sixties, some force-free magnetospheric models have been proposed for pulsars. These are obtained in the ideal MHD approximation, in which one neglects inertial, collisional and gravitational terms, due to the overwhelming electromagnetic forces. We present some results of a numerical relaxation approach, similar to the magnetofrictional method, widely used in modeling the solar corona [1]. Our code provides axisimmetric force-free configurations, in which the geometry of the current distribution and the toroidal magnetic field is generally different from the self-similar solutions presented in [2], [3]. We estimate the effects of resonant Compton scattering through the magnetosphere of magnetars and we discuss how their observed spectra are affected by different geometries of force-free configurations.

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Using very-faint X-ray transients to probe ultra-dense matter in neutron stars

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Very-faint X-ray transients have atypical (low) X-ray luminosities of 10^{34} to 10^{36} erg s^{-1}. Therefore the resulting instantenous (during outburst) as well as the long-term averaged (over thousands of years) accretion rate is very low compared to the normal, brighter transients. Many very-faint X-ray transients have been found to harbor neutron stars. Those systems can therefore be used to probe ultra dense matter in neutron star X-ray binaries in a so-far hardly explored accretion rate regime. I present a short overview of our knowledge of these systems and what we can learn from them, focusing on their expected type-I X-ray burst behavior and their quiescent properties. In addition, it is possible that many harbor accreting millisecond X-ray pulsars. I will also discuss that possibility and how such systems can be used to make progress in understanding fast spinning accreting neutron stars.

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Evolution of neutron stars

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We discuss the most important regulators of thermal evolution of neutron stars such as neutrino emission processes, heat capacity and superfluidity in neutron star cores as well as thermal conduction in heat blanketing envelopes. We analyze which regulators affect the thermal evolution of neutron stars at different evolutionary stages and which properties of neutron stars and their dense matter can be inferred or constrained by comparing thermal evolution theory with observations of thermal radiation from neutron star surface. A special attention is paid to cooling of middle aged isolated neutron stars at the neutrino cooling stage and to determination of their neutrino cooling rates. Available results, obtained by comparing observations with thermal evolution theories, are summarized. The prospects to develop a model-independent method to analyze the data are outlined.

This work was supported by the Russian Foundation for Basic Research (grants 11-02-00253, 11-02-12082-ofi-m-2011), Rosnauka (grant NSh 3769.2010.2), Ministry of Science and Education of Russia (contract 11.G34.31.0001), Dynasty Foundation, and RF Presidential Program (grant MK-5857.2010.2).

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Spectra evolution of type-I X-ray bursts in LMXB 4U 1636–53

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Type-I X-ray bursts are due to unstable burning of H and He on the surface of accreting neutron stars in low-mass X-ray binaries (LMXBs). One of the best studied sources of X-ray bursts is the LMXB 4U 1636–53. Here we present a complete analysis of all X-ray bursts of this source observed to date (300 at the time of writing) with the Rossi X-ray Timing Explorer. From fits to time-resolved spectra with a blackbody model, we found that on average the X-ray bursts in 4U 1636–53 do not follow the $L \propto T^4$ relation. We did a statistical study of the fitted blackbody temperature of X-ray bursts at different flux levels during the cooling phase of X-ray bursts. The distribution of blackbody temperatures for different types of bursts shows significant differences at low flux levels, depending on the nature of the bursts (PRE or non-PRE) and on the properties of the persistent emission of the source at the time of the bursts. We calculated the color correction factor (f_c) as a function of luminosity for different bursts, and from that we deduced changes in the chemical composition of the burning material for different classes of bursts. We also analyzed the super burst in 4U 1636–53 and compared the results of this analysis with the case of normal type-I X-ray bursts. Finally, we explored fits to X-ray bursts of this and other sources using realistic neutron-star atmosphere models to try to constrain the neutron-star equation of state.

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