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RADIATION AND MATTER INTERACTION IN STRONG MAGNETIC FIELD OF ACCRETING NEUTRON STARS

Alexander Mushtukov

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University of Turku

Faculty of Mathematics and Natural Sciences
Department of Physics and Astronomy

Supervised by

Prof. Juri Poutanen
University of Turku
Finland

Dr. Sergey S. Tsygankov
University of Turku
Finland

Prof. Dmitrij I. Nagirner
St. Petersburg State University
Russia

Reviewed by

Prof. Konstantin Postnov
Moscow State University
Russia

Prof. Andrea Santangelo
Universität Tübingen
Germany

Opponent

Prof. Dong Lai
Cornell University
USA

The originality of this thesis has been checked in accordance with the University of Turku quality assurance system using the Turnitin OriginalityCheck service.

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Turku, September 2015 Alexander Mushtukov

Contents

Abstract

This thesis focuses on the theoretical study of radiation and matter interaction in the vicinity of strongly magnetized neutron stars (NSs). NSs give us a unique possibility to study physical processes in such extreme conditions (huge temperatures, densities and magnetic fields) which by no means can be reached in terrestrial laboratories. The enormous strengths of NS magnetic fields ($10^{11} - 10^{15}\,\mathrm{G}$) exceed values achieved by mankind by 10 orders of magnitude. As a result NSs permit us to study experimentally those areas of physics which have been attainable only by theoreticians. Emission that bears the imprint of "radiation-matter" interaction is generated by accretion of matter onto a compact object – one of the most powerful energy release mechanism. If the accretor is a NS, at least 10% of the rest mass energy of the infalling matter is converted into radiation. Gravitational energy of the accreted matter is released in the form of X-rays coming from the area on the surface of the NS close to the magnetic poles where the matter is stopped and heated to very high temperatures ($10^7 - 10^8\,\mathrm{K}$). If the accreting NS is highly magnetized and the magnetic axis is misaligned with respect to the rotational axis of the star, the observed X-ray flux will be modulated with the stellar spin period leading to the phenomenon of an X-ray pulsar (XRP).

We have started studies from analysis of photon scattering by electrons in strong magnetic field, called Compton scattering. This process was examined using quantum electrodynamics and quantum kinetics. We have generalised already known results and offered a basis for accurate calculation of radiation transfer in strong magnetic field. A code for calculation of the scattering cross-section in strong B-field has been developed.

Compton scattering is the major process which defines the radiation pressure in the vicinity of magnetized NSs and the spectral formation. Using the knowledge about the scattering process we have taken a look at the accreting magnetized NS in a wide luminosity range (from $\sim 10^{35}\,\mathrm{erg\,s^{-1}}$ up to $\sim 10^{40}\,\mathrm{erg\,s^{-1}}$). Some basic theoretical ideas were formulated long ago, but the accurate solutions were put off because it was not possible to check the theoretical results. Nowadays the situation is different, we have a good chance to move forward and to test the whole paradigm of XRPs. It will also give us a new opportunity of NSs diagnostics.

We have proposed new XRP models for the main contributing processes

which form their observed spectra. Our models explain the observed positive and negative correlations between the cyclotron line centroid energy and luminosity in the spectra of sub- and super-critical XRPs. We performed accurate calculations of the critical luminosity value, which is necessary to stop the matter above the NS surface due to the radiation pressure. If the luminosity exceeds the critical value, the accretion columns arise above NS surface. Nowadays we are in situation when the observational detection of the critical luminosity could come soon. In order to obtain the maximum accretion luminosity of magnetized NSs we developed theory of super-critical XRPs. A simplified model of the accretion column in the diffusion approximation was constructed and successfully applied for the explanation of a recently discovered pulsating ultraluminous X-ray source X-2 in galaxy M82. Thus we examined accreting highly magnetized NSs in their extreme condition. We have shown that the NS in the particular case of M82 X-2 has an extremely high surface field strength $\sim 10^{14}\,\mathrm{G}$. This estimation have been confirmed independently by detecting the propeller regime of accretion in this source. We have also proposed that a significant part of ultraluminous X-ray sources are accreting highly magnetized NSs.

Tiivistelmä

Tämä väitöskirja tutkii aineen ja säteilyn vuorovaikutusta neutronitähtien läheisyydessä. Neutronitähdet mahdollistavat äärimmäisten fysikaalisten prosessien tutkimisen ympäristössä jota ei ole mahdollista saavuttaa maanpäällisissä laboratorioissa. Esimerkiksi näiden tähtien havaittu magneettikenttä ($10^{11} - 10^{15}\,\mathrm{G}$) ylittää ihmiskunnan saavuttamien kenttien voimakkuuden jopa kymmenellä kertaluokalla. Näin ollen voimme vihdoin tutkia fysiikan ääri-ilmiöitä luonnossa ja avata tietämystämme prosesseista jotka aiemmin olivat vain teoreetikkojen saavutettavissa. Materian pudotessa neutronitähteen, ainakin 10% sen lepomassasta vapautuu säteilynä ympäristöön. Tämä materian gravitaatioenergia vapautuu röntgensäteilynä läheltä magneettisia napoja. Jos tällaisen tähden magneettikenttä on hyvin suuri ja magneettinen akseli poikkeaa pyörimisakselista näemme periodisia modulaatioita röntgensäteilyn kirkkaudessa. Tällaista neutronitähteä kutsutaan pulsariksi.

Tutkimuksemme aloitettiin siitä miten fotoni siroaa elektronista (Comptonin sironta) hyvin vahvassa magneettikentässä. Tätä prosessia tutkittiin kvanttielektrodynamiikan ja -kinetiikan avulla. Olemme sitten yleistäneet aiemmin johdettuja tuloksia ja rakentaneet teoreettisen perustan säteilyn siirtymiselle vahvassa magneettikentässä. Lopuksi olemme kehittäneet koodin sironnan vaikutusalan laskemiseen.

Comptonin sironta on pääosin vastuussa säteilypaineesta ja spektrin muodostumisesta magnetoituneiden neutronitähtien läheisyydessä. Käyttäen aiemmin mainittua tietoa sironnasta, olemme tutkineet magnetoituneita neutronitähtiä suurella luminositeettiskaalalla aina arvosta $\sim 10^{35}\,\mathrm{erg\,s^{-1}}$ arvoon $\sim 10^{40}\,\mathrm{erg\ s^{-1}}$. Olemme myös esitelleet uuden mallin röntgenpulsareiden spektrinmuodostukselle. Mallimme pystyy selittämään positiivisen sekä negatiivisen korrelaation syklotroniviivan energian ja luminositeetin välillä sekä ali- että yli-kriittisille pulsareille. Olemme myös laskeneet tarkasti kriittisen luminositeetin joka vaaditaan materian pysäyttämiseksi säteilypaineella. Jos säteilyn luminositeetti ylittää tämän arvon, niin putoavasta materiasta muodostuva kertymäpylväs kasvaa neutronitähden pinnalle. Näinä päivinä havaintomme ja havaintolaitteemme kehittyvät sitä vauhtia että pystymme pian mittaamaan tämän kriittisen luminositeetin. Jotta pystyisimme selittämään maksimaalisen kertymäluminositeetin, olemme myös kehittäneet teorian yli-kriittisille röntgenpulsareille. Yksinkertaistettu kertymäpylväsmalli formuloitiin käyttäen diffuusioapproksimaatiota ja mallia sovellettiin vasta löydettyyn ultrakirkkaaseen röntgenkohteeseen X-2 galaksissa M82. Käyttäen tätä mallia, olemme mitanneet X-2:ssa sijaitsevan neutronitähden magneettikentän voimakkuudeksi $\sim 10^{14}\,\mathrm{G}$. Tämä mittaus on sen jälkeen todistettu käyttäen myös muita metodeja. Olemme myös ehdottaneet että suuri osa havaituista ultrakirkkaista röntgenkohteista on itseasiassa tällaisia voimakkaasti magneettisia neutronitähtiä.

List of the original publications

Paper I: A.A. Mushtukov, D.I. Nagirner, J. Poutanen, 2015, *Compton scattering S-matrix and cross section in strong magnetic field*, submitted to Phys.Rev.D

Paper II: A.A. Mushtukov, D.I. Nagirner, J. Poutanen, 2012, *Relativistic kinetic equation for Compton scattering of polarized radiation in strong magnetic field*, Phys. Rev. D, 85, 103002

Paper III: A.A. Mushtukov, S.S. Tsygankov, A.V. Serber, V.F. Suleimanov, J. Poutanen, 2015, *Positive correlation between the cyclotron line energy and luminosity in sub-critical X-ray pulsars: Doppler effect in the accretion channel*, accepted for publication in MNRAS, arXiv:1509.05628

Paper IV: A.A. Mushtukov, V.F. Suleimanov, S.S. Tsygankov, J. Poutanen, 2015, *The critical accretion luminosity for magnetized neutron stars*, MNRAS, 447, 1847

Paper V: J. Poutanen, A.A. Mushtukov, V.F. Suleimanov, S.S. Tsygankov, D.I. Nagirner, V. Doroshenko, A.A. Lutovinov, 2013, *A reflection model for the cyclotron lines in the spectra of X-Ray pulsars*, ApJ, 777, 115

Paper VI: A.A. Lutovinov, S.S. Tsygankov, V.F. Suleimanov, A.A. Mushtukov, V. Doroshenko, D.I. Nagirner, J.Poutanen, 2015, *Transient X-ray pulsar V0332+53: pulse phase-resolved spectroscopy and the reflection model*, MNRAS, 448, 2175

Paper VII: A.A. Mushtukov, V.F. Suleimanov, S.S. Tsygankov, J. Poutanen, 2015, *On the maximum accretion luminosity of magnetized neutron stars: connecting X-ray pulsars and ultraluminous X-ray sources*, accepted for publication in MNRAS, arXiv:1506.03600

Paper VIII: S.S. Tsygankov, A.A. Mushtukov, V.F. Suleimanov, J. Poutanen, 2015, *Propeller effect in action in the ultraluminous accreting magnetar M82 X-2*, submitted to MNRAS, arXiv:1507.08288

Chapter 1

Introduction

It is obvious nowadays that quantum processes are very important to understand the physics of a number of astrophysical objects as well as for the understanding of the processes in the early Universe (Raffelt, 1996). Extreme conditions, including high temperature and density as well as strong electromagnetic fields, affect the quantum processes. Extreme conditions can also intensify some processes or even make some of them possible, like it happens with photon splitting, which is forbidden in vacuum but becomes possible in strong magnetic field (Adler, 1971; Harding and Lai, 2006). Study of quantum processes in extreme conditions helps to understand extreme astrophysical objects and vice versa our knowledge about extreme astrophysical objects allow us to check physics inaccessible at terrestrial laboratories. In this thesis I will focus on the effects of strong magnetic fields.

The B-field has to be really strong to affect the quantum processes. There is a natural magnetic field scale given by the so-called critical (Schwinger) field strength $B_{\rm cr} = m_{\rm e}^2 c^3/(e\hbar) \simeq 4.413 \times 10^{13}\,{\rm G}$. It is already known that fields of comparable and even higher strengths exist in the Universe. They are associated with neutron stars. Actually our ideas on strong magnetic fields have changed during last decades: B-fields of order of $10^9 - 10^{11}\,{\rm G}$ were considered as extremely strong fifty years ago (Zeldovich and Novikov, 1971). Nowadays fields of strength of $10^{12}-10^{13}\,{\rm G}$ are considered as medium intensity fields, typical for old NSs (Harding, 2013). Moreover, it has been predicted from theory that NSs can be associated with much stronger magnetic fields ($B >\gtrsim 10^{14}\,{\rm G}$) when they are born (Duncan and Thompson, 1992; Medvedev and Poutanen, 2013) and nowadays we observe objects (magnetars) with such strong B-fields (Olausen and Kaspi, 2014). However, observed NS magnetic field strengths are lower than the theoretical upper limit for NSs $B_{\rm max} \sim 10^{18} - 10^{19}\,{\rm G}$ (Chandrasekhar and Fermi, 1953; Lai and Shapiro, 1991) and much lower than the maximum B-field allowed by quantum electrodynamics that is $B_{max}^{QED} \approx 10^{42}\,{\rm G}$ (Shabad and Usov, 2006a,b). Nevertheless, NSs magnetic fields are much stronger than the fields available in terrestrial laboratories, where we get pulsed B-field of $\sim 10^6\,{\rm G}$ only

(Boyko et al., 1999).

It is also discussed that much stronger B-fields $\sim 10^{23}\,\mathrm{G}$ (Vachaspati, 1991) existed in the early Universe after the phase transition of Quantum chromodynamics ($\sim 10^{-5}\,\mathrm{sec}$) and before the Big Bang nucleosynthesis phase ($\sim 10^{-2}\,\mathrm{sec}$). These strong primordial magnetic fields might cause current large-scale ($\sim 100\,\mathrm{kpc}$) B-fields of strength of $\sim 10^{-21}\,\mathrm{G}$. The field reinforced by dynamo mechanism leads to the observed galactic magnetic field $\sim 10^{-6}\,\mathrm{G}$ (Grasso and Rubinstein, 2001).

This thesis is devoted to the study of radiation and matter interaction in strong magnetic field of accreting NSs. I am focusing on one of the most important processes of interaction between radiation and matter – Compton scattering. Starting from pure physical analyses based on quantum electrodynamics and quantum kinetics (see Chapter 2) I proceed with the research of accretion onto highly magnetised NSs – X-ray pulsars (see Chapter 3), where the special effects of magnetic Compton scattering play a key role.

Chapter 2

Radiation and matter interaction in strong magnetic field

2.1 Matter and radiation in strong magnetic fields

Magnetic fields of sufficiently high strength change the basic properties of matter and affect the processes of interaction between matter and radiation, which in an astrophysical context is particularly important for radiation transfer and affects significantly radiation pressure.

The motion of charged particles in magnetic field is quantized in Landau levels. Only the longitudinal (parallel to the field) momentum of the particle changes continuously, while the motion of a charged particle across the magnetic field is restricted to circular orbits, corresponding to a set of discrete quantum states. In the non-relativistic theory, the distance between Landau levels equals the cyclotron energy $E_{\rm cycl} = \hbar eB/(m_{\rm e}c)$, while in the relativistic theory, Landau level energies equal $E_{\rm n} = m_{\rm e}c^2\left(\sqrt{1+2bn}-1\right)$ $(n = 0, 1, 2, 3, ...)$, where $b = B/B_{\rm cr}$ is the magnetic field strength in units of the critical field strength. The Landau quantization is important when the electron cyclotron energy is comparable to both the electron Fermi energy ϵ_F in the NS atmosphere and the characteristic thermal energy $k_{\rm B}T$. If the cyclotron energy is much larger, then most electrons occupy the ground Landau level in thermodynamic equilibrium and take part in the 1-dimensional motion along the B-field lines. The necessary conditions for that are sufficiently small mass density

$$\rho < \rho_{\rm B} = \frac{m_{\rm i}}{\pi^2\sqrt{2}a_{\rm m}^3 Z} = 7045\frac{A}{Z}B_{12}^{3/2}$$

and $\zeta_{\rm e} \gg 1$, where

$$\zeta_{\rm e} = \frac{E_{\rm cycl}}{k_{\rm B}T} = 134.34\frac{B_{12}}{T_6},$$

where $m_{\rm i}$, Z, A are the ion mass, charge and atomic mass, $a_{\rm m} = (\hbar c/(eB))^{1/2}$ is a typical spatial scale of the electron wave function in the magnetic field

(Potekhin, 2014), $B_{12} \equiv B/10^{12}\,\mathrm{G}$ and $T_6 \equiv T/10^6\,\mathrm{K}$. These conditions are satisfied in the atmospheres of NSs in case when $B \gtrsim 10^{11}\,\mathrm{G}$. The quantization also has to be taken into account in calculations of the accretion flow dynamics in highly magnetized NSs in binary systems (Gnedin and Sunyaev, 1973a, 1974).

2.2 Compton scattering in strong magnetic field

Compton scattering is one of the most important processes of the interaction between radiation and matter in a number of astrophysical objects. In the context of stellar physics and physics of compact objects it affects significantly the observed spectra (Illarionov and Syunyaev, 1972; Sunyaev and Titarchuk, 1980; Becker and Wolff, 2007) and dynamics of a number of processes because it causes largely the radiation pressure (Gnedin and Sunyaev, 1973a; Mitrofanov and Pavlov, 1982; Mushtukov et al., 2015c; Tsygankov et al., 2006; Staubert et al., 2007). In a case of strong B-field the scattering has special features, which make it different from the non-magnetic case. These special features are essentially important for understanding of the processes in the vicinity of magnetized NS (Nagase et al., 1991; Ho and Lai, 2003; Watts et al., 2010; Suleimanov et al., 2009; Poutanen et al., 2013; van Putten et al., 2013)

2.2.1 Electrodynamics

In non-relativistic and non-magnetic case the scattering is characterized by the Thomson scattering cross-section

$$\sigma_\mathrm{T} = \frac{8\pi}{3}\left(\frac{e^2}{m_\mathrm{e}c^2}\right)^2 \approx 6.65\times 10^{-25}\,\mathrm{cm}^2.$$

According to the relativistic solution Compton scattering is described by the Klein-Nishina-Tamm cross-section (Klein and Nishina, 1929; Tamm, 1930) and depends on the parameter $x = (2E/m_\mathrm{e}c^2)\gamma(1-\mu\beta)$, where E is the energy of the initial photon, $\gamma = (1-\beta^2)^{-1/2}$ and $\beta = v/c$ are the electron Lorentz factor and dimensionless velocity correspondingly, $\mu = \cos\Theta$ is the cosine of the angle between photon and electron momenta before the scattering. In the non-relativistic limit ($x \ll 1$) the scattering cross-section is $\sigma \simeq \sigma_\mathrm{T}(1-x)$, while in ultra-relativistic limit ($x \gg 1$) $\sigma \simeq (3/4)\sigma_\mathrm{T}x^{-1}(\ln x + 1/2)$ (see Fig. 2.1). Photons of low energy are scattered into different directions according to Rayleigh law:

$$\mathrm{d}\sigma(\theta) = \frac{3}{8}\sigma_\mathrm{T}(1+\cos^2\theta)\sin\theta\mathrm{d}\theta,$$

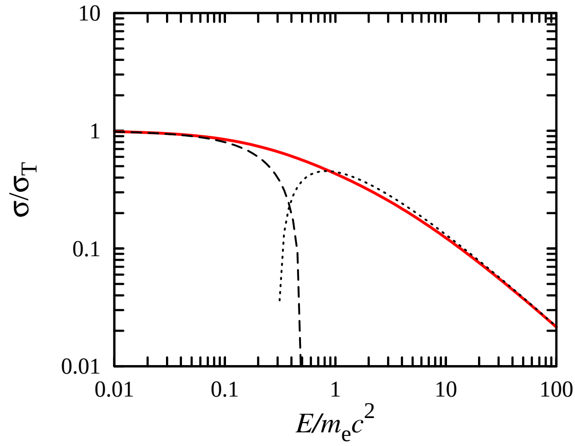

Figure 2.1. Non-magnetic Compton scattering cross-section. Non-relativistic and ultra-relativistic approximations are given by dashed and dotted lines, respectively.

where θ is the angle between the initial and final photon momentum. For high energy photons ($E \geq m_e c^2$) the probability of forward scattering increases (Nagirner and Poutanen, 1994).

Strong external magnetic field significantly affects the properties of the scattering (Harding and Lai, 2006): the interaction cross section becomes strongly dependent on energy, direction of photon momentum and polarization. The latter is represented in terms of two polarization modes: O- and X-mode, where the photon electric vector parallel or perpendicular to the plane formed by the photon momentum and the B-field direction, respectively. The cross-section also depends on the magnetic field strength. A number of resonances corresponding to electron transitions between the Landau levels appear. The resonant cross section value may exceed the Thomson scattering cross section σ_T by more than a factor of 10^6 (see Fig. 2.2).

The simplest expressions for the Compton scattering cross-section in strong B-field was derived in non-relativistic limit (Canuto et al., 1971; Blandford and Scharlemann, 1976):

$$\sigma_O = \sigma_T \left(\sin^2\theta + \frac{1}{2}\cos^2\theta \left[\frac{E^2}{(E+E_{cycl})^2} + \frac{E^2}{(E-E_{cycl})^2} \right] \right),$$

$$\sigma_X = \frac{\sigma_T}{2} \left(\frac{E^2}{(E+E_{cycl})^2} + \frac{E^2}{(E-E_{cycl})^2} \right)$$

for the O- and X-mode respectively. However, the non-relativistic treatment is limited to dipole radiation and therefore only scattering at the cyclotron fundamental is allowed. The non-relativistic approach works well when $E\gamma \ll m_e c^2$. At higher energies the relativistic effects become important

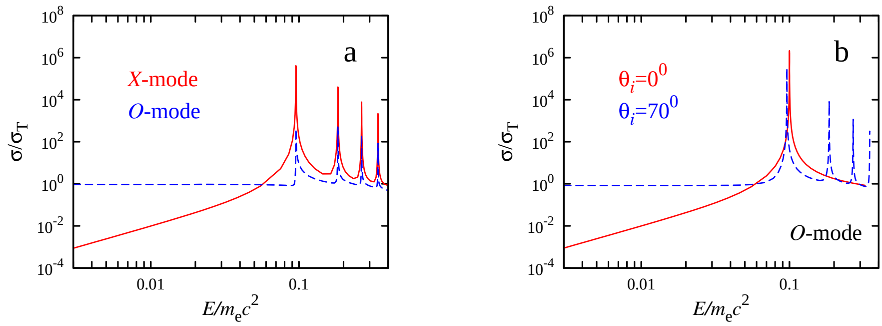

Figure 2.2. The cross section dependence on photon energy. (a) The cross section for the X- and O-mode photons which propagate across the magnetic field ($\theta_i = \pi/2$) are given by solid red and dashed blue lines correspondingly. The cross section below the first resonance shows completely different behaviour. The resonance positions are almost the same, but the cross section of the resonant scattering is also different. (b) The dependence of scattering cross section on the direction. Here $b = 0.1$ (from Mushtukov et al. 2015).

(Klein and Nishina, 1929; Tamm, 1930). The non-relativistic treatment is also limited to the magnetic field strengths of $B \lesssim 10^{12}\,\mathrm{G}$ because electron recoil becomes significant for higher B (Daugherty and Ventura, 1978).

Relativistic quantum electrodynamics (QED) allows us to describe scattering at higher harmonics and scattering which leads to electron transition to higher levels. A QED treatment is the only way to describe accurately scattering at high energies and in strong magnetic field $B \gtrsim 10^{12}\,\mathrm{G}$, which is typical for NSs.

A number of calculations of Compton scattering cross-section in magnetic field were performed for different special conditions. The particular case of Compton scattering with both initial and final electrons on the ground Landau level of zero initial velocity was discussed by Herold (1979). Then the scattering cross section to an arbitrary excited state was calculated by Daugherty and Harding (1986) and by Mészáros (1992). However, these QED calculations assumed infinitely long-lived intermediate state and, therefore, are more relevant to photon energies far from the resonances. In order to calculate the resonant cross section one has to introduce a finite lifetime or decay width to the virtual electrons for cyclotronic transitions to lower Landau levels (Pavlov et al., 1991; Nagirner and Kiketz, 1993). For the specific case of ground-state to ground-state transition in the electron rest frame, Gonthier et al. (2014) showed that the commonly used spin-average width of Landau levels does not correctly account for the spin dependence of the temporal decay and results in a wrong value of the resonant cross section.

Scattering from the ground Landau level is commonly used as a basic approach in case of a strong field: $\hbar eB/(m_\mathrm{e}c) > k_\mathrm{B}T$, when the majority of electrons occupy the ground energy level (Pavlov et al., 1989; Nagase et al., 1991; Baring and Harding, 2007; Nobili et al., 2008; Watts et al., 2010; Chistyakov and Rumyantsev, 2006; Poutanen et al., 2013; Mushtukov et al., 2015c).

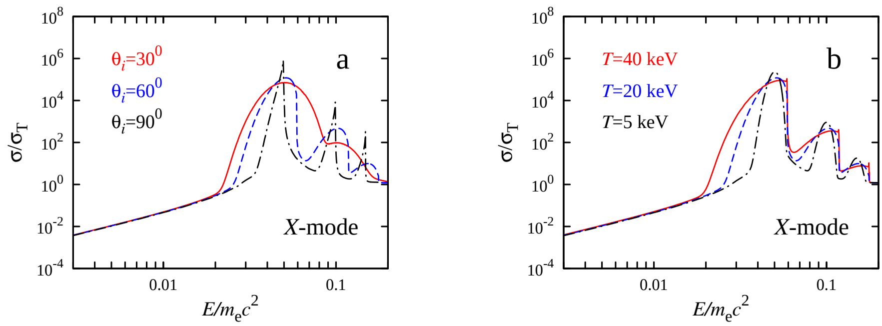

Figure 2.3. The cross section for the X-mode photons as a function of photon energy. (a) Dependence on the angle between the B-field and photon momentum θ_i for fixed electron temperature $T = 20\,\mathrm{keV}$. (b) Dependence on electron temperature (for fixed $\theta_i = 60^0$). The results are given for $b = 0.05$ ($B \simeq 2.2 \times 10^{12}$G) (from Mushtukov et al. 2015).

Moving electrons scatter the photons differently because of relativistic effects. The electron distribution over momentum affects the exact cross section and broadens the resonance features (see Fig. 2.3). This effect could be important for formation of spectral features in X-ray pulsars (Nishimura, 2008, 2011) and for the estimations of radiation pressure (Gnedin and Sunyaev, 1973a; Mitrofanov and Pavlov, 1982). The Doppler broadening depends on the direction (see Fig. 2.3a) because electrons take part mostly in a motion along the B-field lines (Harding and Daugherty, 1991; Mushtukov et al., 2012). The scattering cross section for the case of thermal electrons was calculated and compared with cyclotron absorption by Harding and Daugherty (1991).

According to QED, the scattering process is described completely by its scattering matrix (S-matrix) only (Blandford and Scharlemann, 1976; Berestetskii et al., 1971), which contains the information about the probability amplitudes for the scattering. The transition probabilities and the effective cross sections of the various possible scattering are obtained from the S-matrix elements (which are complex numbers in general) as its squares, and therefore contain less information. The scattering cross sections are sufficient for a number of aims though, but the complete S-matrix is needed for general relativistic kinetic equation (Mushtukov et al., 2012).

2.2.2 Kinetics

The transport of photons through the extended medium involves multiple scattering. This must be taken into account either by the Monte Carlo methods or using the kinetic equations. In non-relativistic and non-magnetic case, when the electron and photon distributions are homogeneous and isotropic, the interaction between photon and electron gases is described by the Kompaneets equation (Kompaneets, 1956):

$$\frac{\partial n}{\partial t} = \frac{\sigma_{\rm T} n_{\rm e}}{m_{\rm e} c} \frac{h}{\nu^2} \frac{\partial}{\partial \nu} n u^4 \left(n + n^2 + \frac{k_{\rm B} T_{\rm e}}{h} \frac{\partial n}{\partial \nu} \right),$$

where $n = \varepsilon_\nu c^2/(8\pi h \nu^3)$, ε_ν is differential radiation energy density. If one would use dimensionless frequency x and dimensionless time y:

$$x \equiv \frac{h\nu}{k_{\rm B} T_{\rm e}}, \quad y \equiv \int \frac{k_{\rm B} T_{\rm e}(t)}{m_{\rm e} c^2} \sigma_{\rm T} n_{\rm e} c \, {\rm d}t,$$

the Kompaneets equation takes the simplest form without any parameters:

$$\frac{\partial n}{\partial y} = \frac{1}{x^2} \frac{\partial}{\partial x} x^4 \left(n + n^2 + \frac{\partial n}{\partial x} \right),$$

where the first term in the brackets n describes photon diffusion to lower frequencies (and energy), the second n^2 describes the induced processes and the last $\partial n/\partial x$ describes photon diffusion towards higher frequencies (Nagirner and Poutanen, 1994).

In case of strongly magnetized plasma the interaction becomes much more complicated: the cross-sections are different for different photon polarization states (O- or X-mode) and photon can change its polarization due to scattering (Miller, 1995). In the cold plasma approximation, which assumes coherent scattering, the radiative transfer equation can be formulated as a set of coupled equations for O- and X-modes (Gnedin and Pavlov, 1974). The influence of the electron temperature on the radiation transport and photon energy diffusion can be accounted by the Fokker-Planck approximation. Particularly, it can be accounted by modifying the Kompaneets equation to allow for resonant scattering (Bonazzola et al., 1979). Such a treatment does not account for effects of the photon angular distribution and polarization, though. Photon polarization, however, influences the photon redistribution over the energy (Nagel, 1981a; Pavlov et al., 1989).

It was already mentioned that in a sufficiently strong B-field the radiation can be described in terms of two polarization modes. However, under certain conditions (depending on the field strength, photon energy and momentum) the vacuum resonance is accompanied by the phenomenon of mode collapse and the breakdown of Faraday depolarization (Zheleznyakov et al., 1983; Lai and Ho, 2003; Pavlov and Shibanov, 1979). In this case the two-mode description fails, photon gas has to be described by Stokes parameters and the kinetic equations have to be written in a more appropriate way.

It can be important to take into account variations of the electron distribution function over momentum, Landau levels and spin states. It can be done by the kinetic equation for electron gas, which has to be solved together with the equation for the photon gas.

The exact kinetic theory for magnetized Compton scattering is far ahead of current observational data. The exact magnetized Compton scattering calculations are still waiting to be included in models of NS atmospheres. Nevertheless, the theory of the magnetized scattering can already explain plenty of observational results.

Chapter 3

Accreting highly magnetized neutron stars

3.1 Magnetized neutron stars

NSs are extremely dense ($\rho \sim 10^{15}\,\mathrm{g\,cm^{-3}}$) compact objects which are born during the gravitational collapse of massive ($M \gtrsim 8M_{\odot}$) stars. Their typical masses $M \sim (1 \div 2)M_{\odot}$ and radii $R \approx 10 \div 15\,\mathrm{km}$ make them essentially relativistic objects (Haensel et al., 2007). Extremely high density and strong magnetic field ($\gtrsim 10^{13}\,\mathrm{G}$) make them powerful laboratories of extreme physics.

The first accreting NS was detected in 1962 during the pioneering observations of the sky in the X-ray range, when the bright source Sco X-1 was discovered (Giacconi et al., 1962). However this source was not recognized as a NS and astronomers discovered NS in radio wave range as radio pulsars, which were explained as rapidly rotating NS (Hewish et al., 1968; Gold, 1968). The first estimations of the NS magnetic field strength were based on the measurement of spin-down of radio pulsars, interpreted as rotational energy loss due to emission of magneto-dipole radiation (Gunn and Ostriker, 1969). According to classical electrodynamics, a rotating magnetic dipole loses its energy. As a result the spin period increases. If one knows the current spin period P and the period derivative $\dot{P}$, then the magnetic field strength can be from

$$B \approx 3.2 \times 10^{19} C \sqrt{P\dot{P}}\ \mathrm{G},$$

where $C = R_6^{-3}(\sin\alpha)^{-3}\sqrt{I_{45}}$ for the case of magnetic dipole (Deutsch, 1955), I_{45} is a moment of inertia in units of $10^{45}\,\mathrm{g\,cm^2}$, $R_6 = R/10^6\,\mathrm{cm}$ and α is the angle between magnetic and rotational axes. $C = 1$ is the commonly used value for simple estimations (Manchester and Taylor, 1977). The equation gives the magnetic field strength on the NS equator. Despite the fact that the rotating NS differs from the ideal magnetic dipole due to the electric currents in the magnetosphere, the B-field strength estimation given by the last

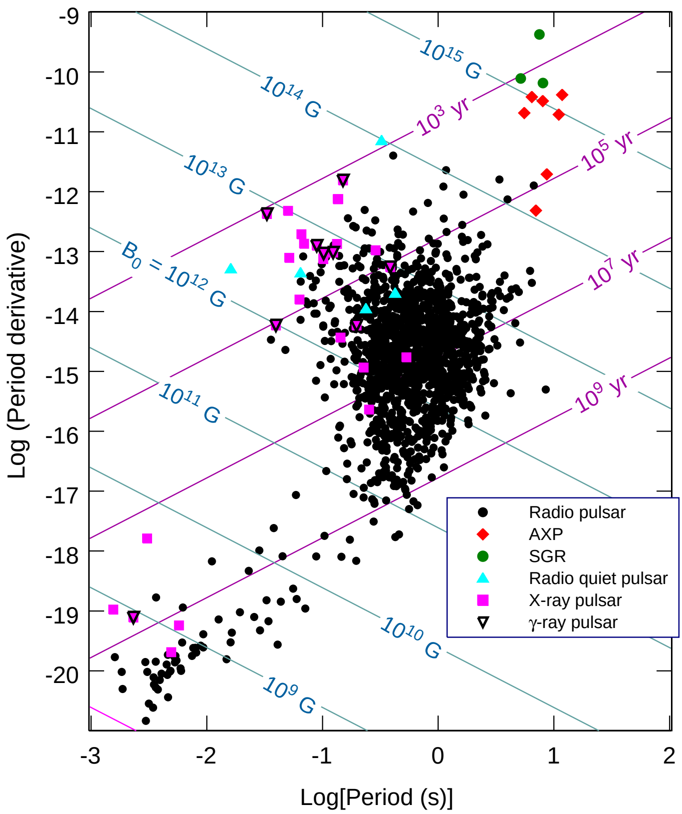

Figure 3.1. Rotation-powered pulsars and magnetars on the plane P vs. $\dot{P}$. Lines of constant characteristic age, given by $P/2\dot{P}$, and surface dipole B-field strength are overplotted (from Harding and Lai 2006).

expression is valid (Beskin et al., 1993, 1983; Beskin, 1999; Michel, 2004; Spitkovsky, 2011). Measurements of P and $\dot{P}$ for radio pulsars show that their surface dipole magnetic field is of the order of $10^{12}\,\mathrm{G}$ (see Fig. 3.1), which was in agreement with earlier predictions based on the assumption that the magnetic flux during the collapse of normal star into NS has to be conserved (Ginzburg, 1964; Woltjer, 1964).

Observations obtained by the UHURU space observatory and discovery of pulsating X-ray sources showed that a number of X-ray binaries contain highly magnetized NSs, where the accretion disc cannot come too close to the compact object. It is interrupted by NS B-field and channeled to the regions close to the magnetic poles, where the energy is released mostly in the X-ray range. In other words, the magnetic field causes the anisotropy of the accretion flow in the vicinity of a star and formation of specific emission pattern, which leads to the phenomenon of X-ray pulsars (XRPs) (Giacconi et al., 1971; Schreier et al., 1972; Tananbaum et al., 1972).

High magnetic fields of XRPs were later confirmed by the other observations. Gnedin and Sunyaev (1973a) pointed out that the spectrum of highly magnetized NS can contain scattering features due to resonant Compton scattering by electrons. The centroid energy of the scattering feature depends on the field strength: $E_{\rm cycl} \simeq 11.6\,B_{12}\,{\rm keV}$, where $B_{12} = B/10^{12}\,{\rm G}$. Therefore, one can find the field strength of the line forming region, if the line is detected in the spectrum. The cyclotron absorption feature was found for the first time in spectrum of XRP Her X-1 at $\sim 42\,{\rm keV}$ (Truemper et al., 1978), which corresponds to $B \simeq 3.5 \times 10^{12}\,{\rm G}$. Nowadays we know a few dozens of XRPs showing cyclotron absorption features in their spectra (see Table 3.1). The majority of cyclotron lines are in a range of few tens keV, which corresponds to magnetic field strength of a few$\times 10^{12}\,{\rm G}$. This magnetic field is comparable with the field of normal radio pulsars (Manchester et al., 2005). It is much higher than the field of known millisecond pulsars, where $B \sim (10^8 - 10^{10})\,{\rm G}$ (Lorimer, 2008) and much lower then the field of known magnetars, where the surface magnetic field $\gtrsim 10^{14}\,{\rm G}$ according to measured P and $\dot{P}$ (see Fig. 3.1) (Duncan and Thompson, 1992; Popov and Prokhorov, 2002), while the internal field strength is expected to be $\sim 10^{16}\,{\rm G}$ (Dall'Osso et al., 2009).

In this thesis I focus on studies of XRPs. This choice is based on the idea that (i) XRPs are associated with magnetic fields sufficiently strong for special quantum effects (see Chapter 2), (ii) the basic picture of their functioning is well known, (iii) there is plenty of unexplained observational regularities, which might be used as a test for proposed theoretical models.

3.2 X-ray pulsars

XRPs form a special class of the family of accreting NSs. They stand out from the other classes of accreting NSs due to their strong magnetic field ($\gtrsim 10^{12}\,{\rm G}$). The field interrupts the accretion disc at the magnetosphere radius, where the magnetic and plasma stresses balance. The magnetospheric radius is given by:

$$R_{\rm m} = k\left(\frac{\mu^4}{GM\dot{M}^2}\right)^{1/7},$$

where M and μ are the NS mass and magnetic moment, $\dot{M}$ is the mass accretion rate and $k \leq 1$ is a constant which depends on the accretion flow geometry ($k = 1$ for the case of spherical accretion and $k < 1$ for the case of accretion from the disc, see Ghosh and Lamb 1978, 1979). Inside the magnetosphere radius, the magnetic field channels the gas towards the magnetic poles, where the captured matter releases its gravitational energy as X-ray

Table 3.1. List of XRPs with known cyclotron lines (question mark "?" means marginal detection, see details and corresponding references in Walter et al. 2015). XRPs where the cyclotron line position varies with luminosity are bold typed, it is also specified in brackets a type of variability: negative (−) or positive (+) correlation.

Source name	Cyclotron energy, keV
4U 0115+63 (−)	11.5, 20.1, 33.6, 49.5, 53
V 0332+53 (−)	28, 53, 74
4U 0352+309 (X Per)	29
RX J0440.9+4431	32
RX J0520.5-6932	31.5
A 0535+262	50, 110
MXB 0656–072	36
Vela X-1 (+)	27,54
GRO J1008-57	$88^?$, 75.5
1A 1118–61	55
Cen X-3	28
GX 301–2	37, 48
GX 304–1 (+)	50.8
4U 1538–52	20, 47
Swift J1626.6–5156	10
4U 1626–67	37
Her X-1 (+)	42
OAO 1657–415	36
GRO J1744–28	4.7
IGR J18179–1621	21
GS 1843+00	20
4U 1907+09	19, 40
4U 1909+07	$44^?$
XTE J1946+274	36
KS 1947+300	12.5
EXO 2030+375	$11^?$, $36^?$, $63^?$
Cep X-4	30

radiation. Many questions concerns the interaction of the accretion flow (stellar wind or accretion disc) and NS magnetosphere. Different theoretical models (see Fig. 3.2) predict different $R_{\rm m}$ and different penetration depths of the accretion flow into the NS magnetosphere (Ghosh and Lamb 1979; Shu et al. 1994; Lovelace et al. 1995; Matt and Pudritz 2005a,b, see also Lai 2014 for review). This is important for a self-consistent picture, but beyond the scope of the thesis.

3.2.1 Observations

XRPs belong to class of young objects – High-Mass X-ray Binaries (HMXBs), where the companions are early-type massive ($M > \mathrm{few} \times M_{\odot}$) stars, or to the class of much older (several billion years old) objects – Low-Mass X-ray Binaries (LMXBs), where the donor star is less massive ($M < M_{\odot}$) than the compact object. High mass accretion rates with corresponding accretion luminosities $> 10^{35}\,\mathrm{erg\ s^{-1}}$ in case of HMXBs are observed either during strong and transient X-ray outbursts caused by interaction of compact object with dense component of the stellar wind or when the companion fills its Roche lobe. In the latter (and quite rare) case system becomes very luminous: $L \gtrsim 10^{40}\,\mathrm{erg\ s^{-1}}$ (Bachetti et al., 2014).

The X-ray continuum of XRPs is characterized by a power-law of photon index $0.3 - 2$ with an exponential cuttoff at high energies in general above $7 - 30\,\mathrm{keV}$ (see Fig. 3.3, White et al. 1983; Filippova et al. 2005). The plasma reaches high speed (up to $\sim 0.6\,c$) in the vicinity of a NS and is heated to $10^8\,\mathrm{K}$ (Basko and Sunyaev, 1976; Nishimura, 2008; Mushtukov et al., 2015c). As a result bulk and thermal Comptonization play an important role in the formation of final non-thermal X-ray spectrum (Becker and Wolff, 2007). Physical models for continuum were constructed only for special configurations (Nagel, 1981b,a; Meszaros and Nagel, 1985a,b) of the emission region and are not able to describe in a self-consistent way the observational data. However, in the recent years we have seen progress that highlighted some observational regularities. Particularly the general tendencies of continuum variations with luminosity are found (Klochkov et al., 2011; Reig and Nespoli, 2013) and described (see Fig. 3.4) (Postnov et al., 2015).

A strong magnetic field modifies the observed X-ray spectrum often manifesting itself as the line-like cyclotron absorption features (Coburn et al., 2002; Caballero and Wilms, 2012). The absorption features caused by the Compton scattering of X-ray photons on electrons whose energy is quantised in strong magnetic field (Gnedin and Sunyaev, 1974; Truemper et al., 1978). Since the cyclotron energy can be measured from the observed spectrum of the source, the magnetic field strength in the line forming region can be estimated. It provides a brilliant tool for almost direct measurements of NSs

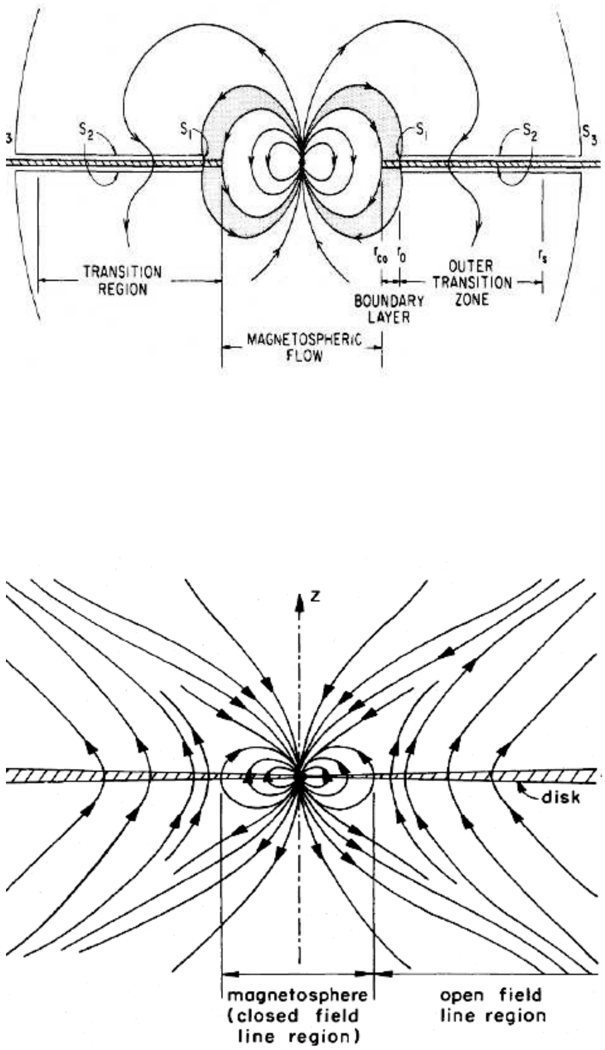

Figure 3.2. Different theoretical models of magnetosphere-disc interaction: top panel - Ghosh & Lamb model (Ghosh and Lamb, 1979), bottom panel - Lovelace model (Lovelace et al., 1995).

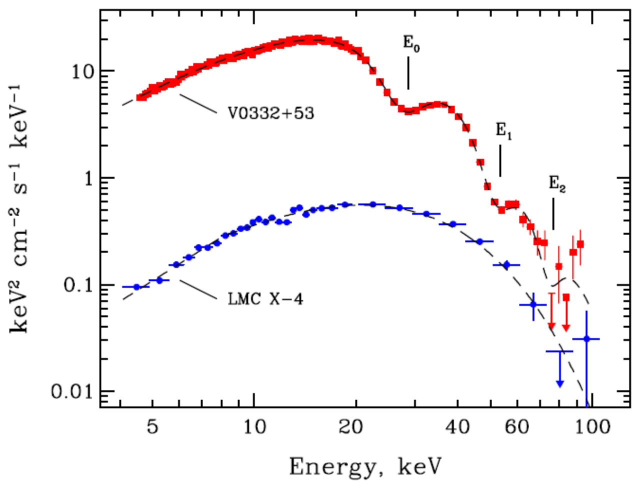

Figure 3.3. Energy spectra of two XRPs obtained by *INTEGRAL*: V0332+53 (red squares) with cyclotron line absorption features and LMC X-4 (blue circles) without such absorption features (from Walter et al. 2015).

magnetic fields. However, it is necessary to understand the location (see for example Doroshenko et al. 2010) and geometry of the line forming region and details of the line formation process.

Cyclotron lines have been found in spectra of more than two dozens of accreting magnetized NSs. In four of them we see higher harmonics (up to the fifth in case of 4U 0115+63) as well (see Table 3.1), which is important as a confirmation of cyclotron nature of the observed features (see Doroshenko et al. 2012).

A number of XRPs exhibit significant variations of the line centroid energy on pulse-to-pulse time scales, and also on much longer time scales (Mihara et al., 2004; Staubert et al., 2007; Tsygankov et al., 2006, 2007, 2010; Klochkov et al., 2012; Fürst et al., 2014; Lutovinov et al., 2015). This clearly indicates that the accretion flow is neither stationary nor uniform.

Different sources exhibit various regularities but it is possible to group them into two classes: sources with relatively low luminosity ($L \lesssim 10^{37}\,\mathrm{erg\,s^{-1}}$) show positive correlation between the line centroid energy and luminosity (Staubert et al., 2007), while bright sources ($L \gtrsim 10^{37}\,\mathrm{erg\,s^{-1}}$) show a negative correlation (Tsygankov et al., 2006). Positive correlation was found first in Her X-1 by Staubert et al. (2007). Authors interpreted this result as being due to the decrease of the height h of the emitting region above the NS surface ($E_{\rm cycl} \propto B$ and $B \propto (R+h)^{-3}$ in case of dipole magnetic field) in the sub-critical regime of the accretion with the increase of the mass accretion rate onto the NS. It is believed that the negative correlation takes place when the radiation pressure becomes large enough to stop the accretion flow

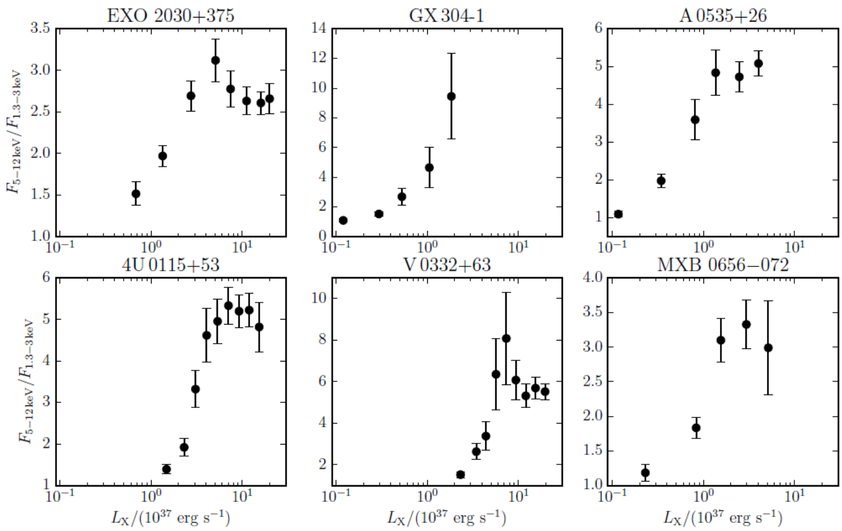

Figure 3.4. The ratio of the fluxes in $5-12$ keV and $1.33-3$ keV ranges measured with RXTE/ASM for six transient accreting pulsars as a function of the total ASM flux in the $1.33-12$ keV range (from Postnov et al. 2015).

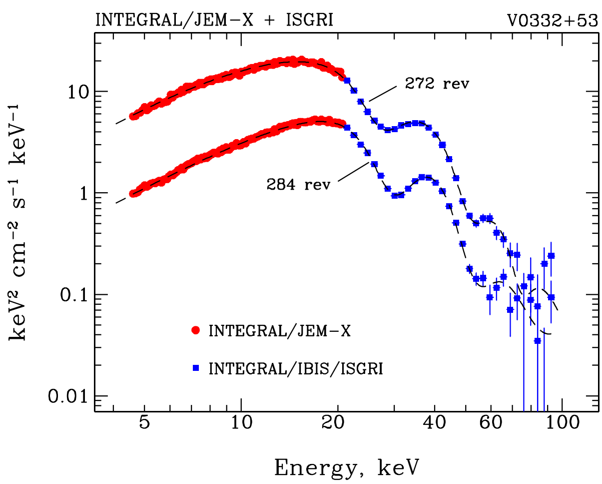

Figure 3.5. Energy spectra of X-ray transient V0332+53 measured with the *INTEGRAL* observatory for two states (272 and 284 revolutions). It is clearly seen that the cyclotron line changes its position with the luminosity (from Tsygankov et al. 2006).

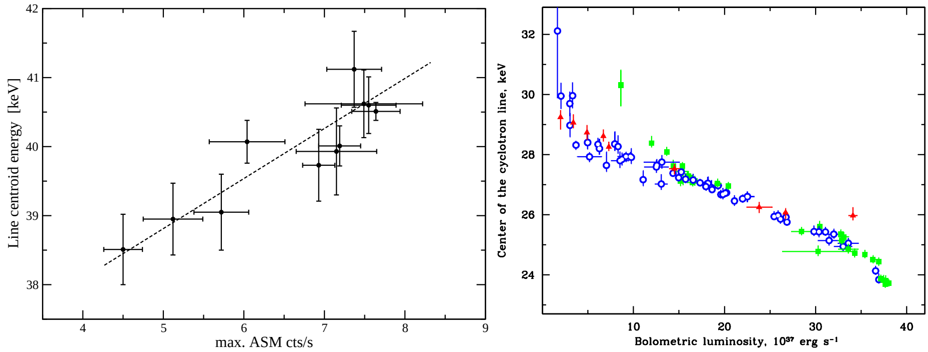

Figure 3.6. Cyclotron line energy dependence on the luminosity for Her X-1 (from Staubert et al. 2007, left), where the line centroid energy is positively correlated with the luminosity, and for V0332+53 (from Tsygankov et al. 2010, right), where the correlation is negative.

above the stellar surface and the accretion column arises. It happens when a pulsar reaches the so-called critical luminosity (Basko and Sunyaev, 1976; Mushtukov et al., 2015c). A direct confirmation of this scenario could be obtained if the same XRP will show both behaviours: with positive correlation in a low luminosity state and with negative correlation in a bright state. The transition of a source from one state to another has not been observed yet and it is a point of observational interest. There are reasons to believe that new observations will be soon available.

Finally, it becomes clear that the cyclotron line analysis provides a great opportunity for the diagnostics of accreting NS physics. It is necessary to have an accurate theory of cyclotron line formation, which includes knowledge about elementary processes, magneto-hydrodynamical calculations and radiation transfer.

3.2.2 Theory of sub-critical and super-critical accretion

The accretion luminosity of XRPs, as it is clearly seen from the observations, can be close or even higher than the Eddington limit $L_{\rm Edd}$, which is commonly used as a restriction of possible isotropic luminosity of the object with a given mass M:

$$L_{\rm Edd} = \frac{4\pi G M m_{\rm H} c}{\sigma_{\rm T}(1+X)} \approx 1.4\times 10^{38}\frac{M}{M_\odot}\ {\rm erg\ s^{-1}},$$

where $m_{\rm H}$ is the hydrogen mass and X is its mass fraction.

The theory of accretion onto magnetized NS is based on two important effects: the accretion flow is channelled by strong magnetic field, which

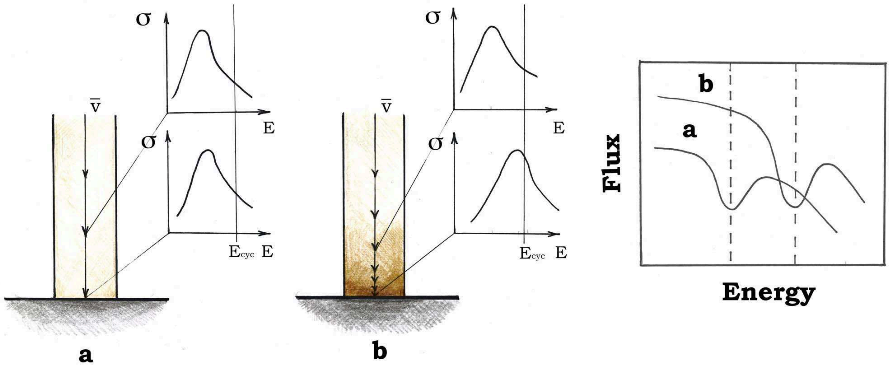

Figure 3.7. The schematic presentation of the dependence of the cyclotron line energy on the velocity profile in the line-forming region of sub-critical XRPs. The radiation pressure affects the velocity profile when the luminosity is approaching its critical value: the higher the luminosity, the lower the velocity in the vicinity of NS surface. The lower the electron velocity, the lower the redshift and the higher the resonant energy at a given height. As a result, a positive correlation between the line centroid energy and the luminosity is expected (from Mushtukov et al. 2015b).

makes the problem essentially non-spherically symmetrical (Basko and Sunyaev, 1976), and the effective cross-section $\sigma_{\rm eff}$ of the interaction between radiation and matter can be much different from the cross-section of the non-magnetic case (Mitrofanov and Pavlov, 1982; Gnedin and Nagel, 1984). Particularly, the scattering cross section can be much lower than $\sigma_{\rm T}$ if the majority of photons have energies below the cyclotron one $E_{\rm cycl} \approx 11.6 B_{12}\,{\rm keV}$, which is possible in sufficiently strong B-fields, and the cross section can also be much higher than $\sigma_{\rm T}$ if the photon energy $\sim E_{\rm cycl}$. Both possibilities affect significantly the radiation transfer and radiation pressure.

At low mass accretion rates ($< 10^{16}\,{\rm g\,s^{-1}}$) radiation pressure has only a minor effect on the infalling material. The accretion flow heats up the NS surface and the total energy flux vanishes on the NS surface: the kinetic energy flux is balanced by the emergent radiation (Lamb et al., 1973; Gnedin and Sunyaev, 1973a; Basko and Sunyaev, 1975; Lyubarskii and Syunyaev, 1982). The observed spectrum is shaped by plasma deceleration in the NS atmospheres (Miller et al., 1987, 1989) and by interaction of already emitted radiation with the accretion flow (Nelson et al., 1993; Mushtukov et al., 2015b).

The higher the mass accretion rate, the higher the radiation pressure. The radiation pressure affects the accretion flow velocity in the very vicinity of NS surface, which influences the cyclotron scattering feature position in the spectrum due to the Doppler effect (Mushtukov et al., 2015b) and explains naturally the positive correlation between the XRP luminosity and the line energy (see Fig. 3.7). At some point mass accretion becomes so high that the matter is stopped by the radiation pressure above stellar surface and an accretion column begins to grow (Basko and Sunyaev, 1976; Mushtukov et al., 2015c). The corresponding luminosity can be estimated as follows (Basko and Sunyaev, 1976):

$$L^* = 4 \times 10^{36} \frac{M/M_\odot}{R_6} \left(\frac{l}{2 \times 10^5 \text{cm}} \right) \frac{\sigma_\text{T}}{\sigma_\text{eff}} \text{ erg s}^{-1},$$

where l is the length of the accretion channel cross-section on the NS surface. The critical luminosity value L^* depends on the surface magnetic field strength due to the strong dependence of the scattering cross-section on the field strength. The critical luminosity is not a monotonic function of B (Mushtukov et al., 2015c) and has its minimum value $\sim (3-5) \times 10^{36}\,\text{erg s}^{-1}$ at B-field strength $\sim 10^{12}\,\text{G}$ (see Fig. 3.8), when the majority of photons have energy close to E_cycl and the effective radiation pressure reaches its maximum value. For higher magnetic field strength the critical luminosity value increases due to decrease of the effective scattering cross-section. For the XRP GX 304–1, where the surface magnetic field is expected to be $\sim 5 \times 10^{12}\,\text{erg s}^{-1}$, it reaches the value of $\sim 2 \times 10^{37}\,\text{erg s}^{-1}$, which is close to the observed luminosity. It was already mentioned that the critical luminosity was already observed for Vela X-1 (Fürst et al., 2014) at $\sim 10^{37}\,\text{erg s}^{-1}$, which is in a good agreement with our theoretical predictions for this source. However, this observational statement remains disputable, since it was based on analysis of the first harmonic behaviour instead of the fundamental.

The physics of super-critical regime of accretion ($L > L^*$) and the structure of the accretion column were discussed in late 1970s ans 1980s (Gnedin and Sunyaev, 1973a; Basko and Sunyaev, 1975, 1976; Lyubarskii and Syunyaev, 1982, 1988). It has been found that the luminosity of highly magnetized NS featuring an accretion column above its surface can be much higher than the Eddington luminosity value, since the radiation pressure is balanced by the strong magnetic pressure, which supports the column. The luminosity of the NS with an accretion column of height H above its surface can be estimated as follows (Mushtukov et al., 2015a):

$$L(H) \approx 38 \left(\frac{l_0/d_0}{50} \right) \frac{\sigma_\text{T}}{\sigma_\perp} f \left(\frac{H}{R} \right) L_\text{Edd},$$

where $f(x) = \log(1+x) - x/(1+x)$, l_0 and d_0 are length and thickness of the accretion channel, $\sigma_\perp$ is the effective Compton scattering-cross section across the magnetic field direction. For a column as high as the NS radius the accretion luminosity becomes:

$$L(H=R) \approx (2 \div 3) \times 10^{39} \left(\frac{l_0/d_0}{50} \right) \frac{\sigma_\text{T}}{\sigma_\perp} \text{erg s}^{-1}.$$

The luminosity of the magnetized NS can reach extremely high values.

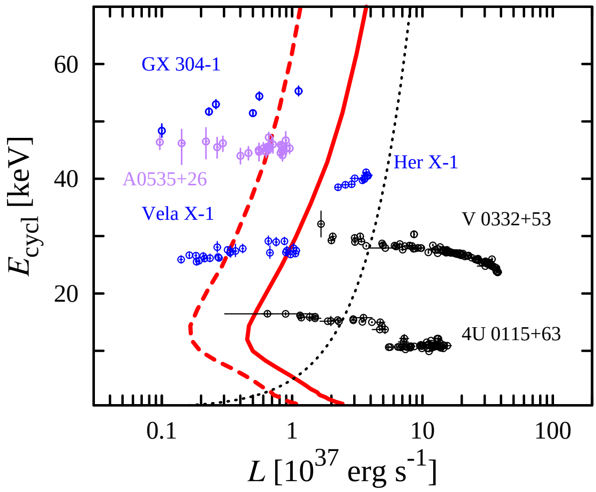

Figure 3.8. Red solid and dashed curves correspond to the disc-accretion case with different parameters (accretion flow geometry and polarization mixture of the radiation). The actual critical luminosity value lies likely between these two curves. The black dotted line shows the predictions by Becker et al. (2012) (from Mushtukov et al. 2015c).

Both critical luminosity and luminosity of the accretion column depend on the geometry of the accretion channel, which in turn is defined by the interaction of the accretion flow with the magnetosphere in general calculated separately (see Semena et al. 2014).

From the comparison of XRPs spectra variability with the theoretical models we can conclude that the height of the accretion column increases with the mass accretion rate and can be as high as the NS radius (Poutanen et al., 2013; Postnov et al., 2015).

The height of the accretion column is obviously limited by the magnetosphere's radius ($H < R_{\rm m}$). However many additional conditions have to be taken into account. The gas and radiation pressure should not be higher than the magnetic pressure. This is important for fields of strength $B \lesssim 2 \times 10^{13}\,{\rm G}$. One can expect that the settling of the accretion flow to the NS surface might be unstable with respect to presence of so-called photon bubbles – the regions with high radiation pressure act like light fluid with respect to heavy fluid of infalling material (Basko and Sunyaev, 1976; Arons, 1992; Klein et al., 1996). It has been predicted that photon bubbles can manifest themselves as quasi-periodic oscillations in time series of X-ray luminosity. However such oscillations have not been found so far (Revnivtsev et al., 2015).

If the magnetic field strength is higher than $\sim 2 \times 10^{13}\,{\rm G}$, the internal column temperature can reach the value of $\sim 10^{10}\,{\rm K}$, when the electron-

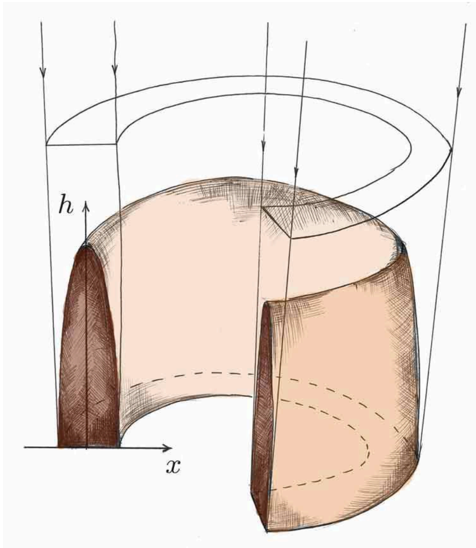

Figure 3.9. A schematic structure of the accretion column: the height of a radiation dominated shock varies inside the accretion channel, since the radiation energy density drops sharply towards the column edges. The accretion column height reaches its maximum inside the channel and decrease towards its borders (from Mushtukov et al. 2015a).

positron pair creation with further annihilation into neutrino and anti-neutrino become important: $e^{+} + e^{-} \longrightarrow \nu_{\rm e} + \overline{\nu}_{\rm e}$ (Beaudet et al., 1967). In this case part of accretion luminosity can be released by neutrino rather than by photons. However, it was shown that the accretion columns above NS with surface B-field strength $\gtrsim 5 \times 10^{13}\,{\rm G}$ cannot be very high and their internal temperature does not reach extreme value (Mushtukov et al., 2015a).

The accretion column structure is very important for the formation of a beam pattern from XRP. According to our current understanding, the height, where the matter is stopped by the radiation dominated shock, varies inside the accretion channel. It is caused by the fact that the radiation energy density drops towards the accretion channel edges. As a result, the height reaches its maximum value in the center of the channel and it decreases towards the edges (see Fig. 3.9). Then the radiation from the already stopped matter has to penetrate through the layer of fast moving plasma. The optical thickness of this layer can be high enough to change the photon distribution of the photons over directions due to scattering by electrons in the accretion flow. Finally, the radiation is beamed towards the NS surface (Kaminker et al., 1976; Lyubarskii and Syunyaev, 1988), intercepted and reprocessed. The radiation reprocessing affects the spectrum properties: the continuum radiation becomes harder (Postnov et al., 2015) and a cyclotron absorption feature appears (Poutanen et al., 2013) according to basic principles of radi-

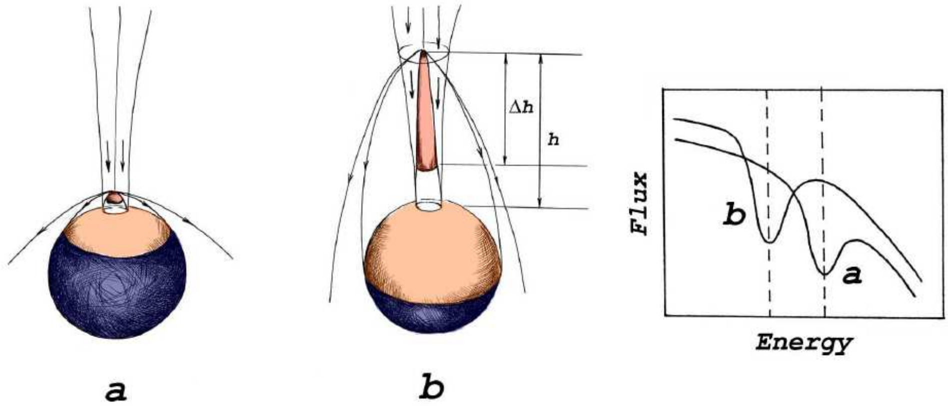

Figure 3.10. The accreting X-ray pulsar geometry in bright luminosity state, accretion column structure, and the emergent spectrum with the cyclotron absorption feature. The larger the mass accretion rate, the higher the column, the larger the illuminated part of the NS surface, the lower the average B-field, and the smaller the cyclotron line centroid energy (from Poutanen et al. 2013).

ation reflection from the semi-infinity medium (Avrett and Hummer, 1965; Avrett et al., 1965; Ivanov, 1973). Changes of the accretion column height and corresponding variability of the illuminated region on the NS surface explains naturally variations of the cyclotron line centroid energy with the accretion luminosity: the higher the mass accretion rate, the higher the column, the lower the magnetic field strength averaged over the illuminated part of the NS, the lower the observed cyclotron line centroid energy (see Fig. 3.10).

One of the most important property of XRPs – their pulse profiles, caused by specific beam pattern, are not explained well so far. The structure of XRPs beam pattern depends strongly on the geometry of the region, where the gravitational energy is radiated (Gnedin and Sunyaev, 1973b). It has to be different for sub-critical and super-critical sources and also has to be affected by the accretion curtain. It is interesting that such profile change has been reported already for XRP Vela X-1 (Doroshenko et al., 2011). Nevertheless, we are quite far from the complete understanding.

3.3 Ultra-luminous X-ray sources as accreting NSs

Ultra-luminous X-ray sources (ULXs) are point-like (unresolved) extragalactic X-ray sources with an observed X-ray luminosity in excess of $L \sim 10^{39}\,\mathrm{erg\,s^{-1}}$, assuming that they radiate isotropically (see Feng and Soria 2011 for review). Typically we observe about one ULX per galaxy, but in some galaxies many ULXs are detected (see Fig. 3.11). The bolometric lu-

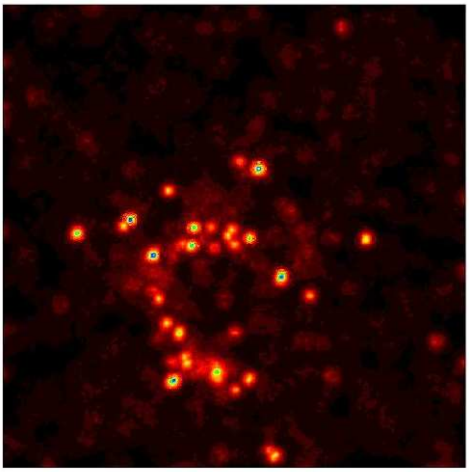

Figure 3.11. Chandra image of the rapidly star forming galaxy NGC4038 (Antenna) with a number of ULXs in it.

minosity of ULXs exceeds the Eddington limit for accretion on a $10M_{\odot}$ black hole (BH). This is indeed intriguing since ULXs may be a possible manifestation of sub-critical accretion onto intermediate-mass (masses in the range $\sim 10^2 \div 10^5 M_{\odot}$) BHs (IMBHs, see Colbert and Mushotzky 1999). Potentially IMBHs can help to understand the way how super-massive BHs have grown to their current masses, and in this sense IMBHs are important for cosmological studies (Ebisuzaki et al., 2001). If ULXs are partly IMBHs, than they form a link between StMBH and super-massive BHs ($M \sim 10^6 \div 10^9 M_{\odot}$). According some models IMBHs can form in the early Universe with or/and from population III stars (Madau and Rees, 2001). It is also possible that IMBH might originate from mergers of stars in dense star clusters (Portegies Zwart et al., 2004).

At the present time their true nature is not well understood and in fact there maybe several types of objects in this category. However, the Eddington limit is normally calculated for the case of spherical accretion and the upper luminosity limit for the case of disc accretion can be much higher. As a result the ULXs might be powered by super-critical accretion onto typical stellar mass ($\sim 10M_{\odot}$) BHs (StMBHs), where the advection (Abramowicz et al., 1988) and massive accretion disc outflow (Shakura and Sunyaev, 1973) can play key role in shaping the accretion flow and final spectrum (Poutanen et al., 2007).

However, it was recently found by the *NuSTAR* observatory that the ULX X-2 in galaxy M82 shows coherent pulsations with an average period of $1.37\,\mathrm{s}$ (Bachetti et al., 2014), which means that the compact object in this particular case is not a BH but a NS. This discovery implies that accreting NS can reach luminosities of about $10^{40}\,\mathrm{erg\,s^{-1}}$, which is two orders of magnitude higher

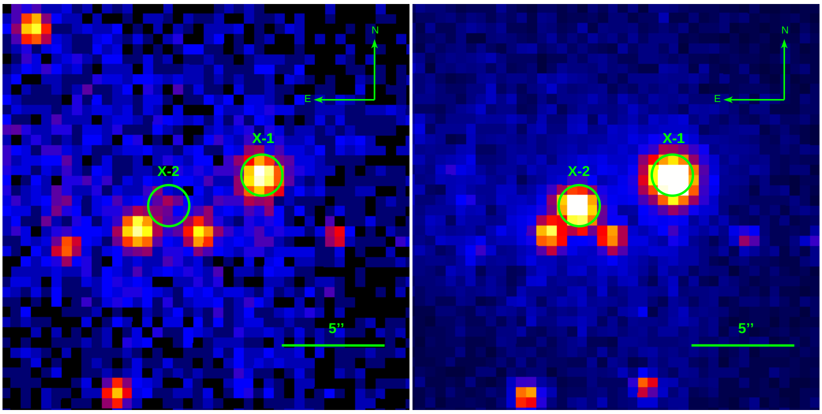

Figure 3.12. Chandra images of M82 galaxys centre during observations performed on September 20, 1999 when M82 X-2 was in a low-luminosity state (left) and August 17, 2005 when it was in a high-luminosity state (right). Circles indicate the positions of M82 X-1 and M82 X-2 ULXs. Note that the sources close to X-2 have constant brightness, while X-2 is much weaker than those during the first observation and much brighter during the second one (from Tsygankov et al. 2015).

than the Eddington limit. In this sense the discovery is a challenge for the theory of accretion onto NSs. Such high mass accretion luminosity can be explained by extremely high NS magnetic field $\sim 10^{14}\,\mathrm{G}$ (Mushtukov et al., 2015a), which reduces the scattering cross section and confines the accretion flow to accretion column (see Section 3.2.2). It is important that it is not enough to explain the way how radiation is emitted in the vicinity of NS, the sufficient mass accretion rate $\sim 10^{20}\,\mathrm{g\,s^{-1}}$ has to be explained as well. It is not a trivial task since the accretion flow has to be very special in this case: the accretion disc is thick and close to the critical regime, when the outflows are important and can regulate effectively the resulting mass accretion rate onto NS (Shakura and Sunyaev, 1973; Lipunov, 1982), the details of interaction with the magnetosphere in these conditions are not quite clear and rise a number of questions.

Nevertheless, it is already confirmed that in this particular case we see accretion onto NS with magnetar-like magnetic field $\sim 10^{14}\,\mathrm{G}$. According to simple estimations, an accreting NS at such high mass accretion rate reaches the spin equilibrium (when the corotation and magnetosphere radii are equal) within a few hundreds years (Lipunov, 1982). As a result small changes in the mass accretion rate lead to dramatic changes of the accretion luminosity due to the so-called "propeller"-effect (Illarionov and Sunyaev, 1975). The mass accretion rate, at which the "propeller"-effect appears, depends on the B-field strength and the last can be estimated from the known mass accretion rate. The "propeller"-effect has been obtained for the ULX M82 X-2 (see Fig. 3.12) and magnetic field $\sim 10^{14}\,\mathrm{G}$ has been successfully

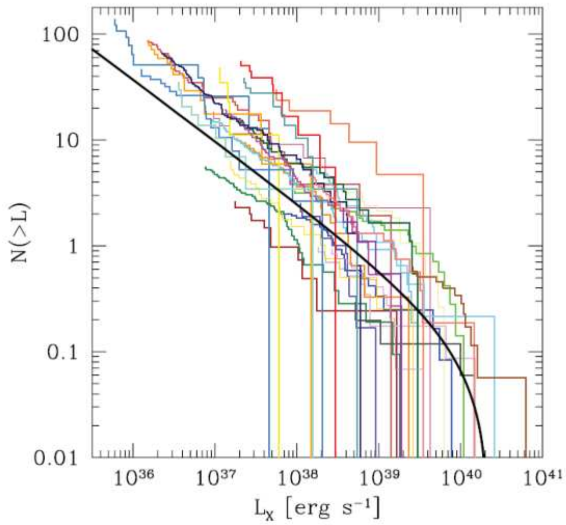

Figure 3.13. Cumulative X-ray luminosity functions (XLFs) of galaxies from the primary sample, normalized by their respective star-formation rates (coloured curves) and theoretical XLF per unit star-formation rate (solid black curve) (from Mineo et al. 2012).

confirmed (Tsygankov et al. 2015).

The discovery of NSs as a compact objects in ULXs puts an additional important question: what part of ULXs are accreting NSs? It is interesting that no other pulsating ULX has been observed yet (see Doroshenko et al. 2015b, where pulsations to some pulse fraction are excluded in most of the ULXs seen by *XMM-Newton*). According to our recent results the accretion luminosity of a few$\times 10^{40}\,\mathrm{erg\,s}^{-1}$ is a good estimation for maximum NS accretion luminosity (Mushtukov et al., 2015a). This luminosity coincides with the cut-off observed in the HMXBs luminosity function (ULXs are taken into account there as HMXB, see Fig. 3.13) which otherwise does not show any features at lower luminosities (Mineo et al., 2012). Therefore one can conclude that a substantial part of ULXs are accreting NSs (Mushtukov et al., 2015a).

Chapter 4

Summary of the original publications

4.1 Paper I – Compton scattering S-matrix and cross section in strong magnetic field

In this paper we have considered Compton scattering of polarized radiation in strong magnetic fields ($B > 10^{11}\,\mathrm{G}$) and in the most general case. The recipe for calculation of the scattering matrix elements, the differential and total cross sections based on QED second order perturbation theory has been investigated and presented for the case of arbitrary initial and final Landau levels, electron momentum along the field, and photon momentum. The photon polarization and electron spin state were taken into account. The correct dependence of the natural Landau level width on the electron spin state was also taken into account. A number of steps in calculations were simplified analytically, which makes the presented recipe quite easy-to-use. This paper generalizes already known results and offers a basis for accurate calculation of radiation transfer in strong B-field, typical for magnetized neutron stars. It also provides a useful tool for further investigation.

4.2 Paper II – Relativistic kinetic equation for Compton scattering of polarized radiation in strong magnetic field

In this paper we have considered Compton scattering in strong magnetic fields from the kinetic point of view. We derived the relativistic kinetic equation for Compton scattering of polarized radiation using the generalized Bogolyubov method. The induced scattering and the Pauli exclusion principle for electrons were taken into account. Special equations for the cases of non-polarized rarefied and dense electron gas were found and compared with already known equations. The derived equations are valid for a wide range of photon and electron energies and magnetic field strength below $\sim 10^{16}\,\mathrm{G}$. These equations can be used for formulation of the equation for polarized radiation transfer in atmospheres of strongly magnetized NSs. A few polarization effects were predicted in the paper as well.

4.3 Paper III – Positive correlation between the cyclotron line energy and luminosity in sub-critical X-ray pulsars: Doppler effect in the accretion channel

In this work we investigate the nature of cyclotron line variations with the luminosity for low-luminous XRPs. The line centroid energy shows positive correlation with the luminosity in this case. We argue that the cyclotron line is formed when the radiation from a hot spot propagates through the layer of moving plasma near the neutron star surface. The changes of the cyclotron line position in the spectrum are caused by variations of the velocity profile in the line forming region due to different radiation pressure at different luminosities. The presented model has several characteristic features: (i) The line centroid energy has to be positively correlated with the luminosity; (ii) The line width has to be positively correlated with the luminosity as well; (iii) The position and width of the cyclotron absorption line are variable over the pulse phase; (iv) The line has a more complicated shape than the widely used Lorentzian and Gaussian profiles; (v) the phase-resolved cyclotron line centroid energy and width are expected to be negatively and positively correlated with the pulse intensity, respectively. The predictions of the proposed theory are compared with the observed variations of the cyclotron line parameters in the XRP GX 304–1 over a wide range of sub-critical luminosities using the *INTEGRAL* data.

4.4 Paper IV – The critical accretion luminosity for magnetized neutron stars

In this paper we have investigated the luminosity which separates accreting NSs featuring a hot spot on their surface from the ones which are bright enough and where then accretion column exists above their surface. This limit luminosity is usually called the “critical luminosity”. We have calculated the critical luminosity as a function of the NS surface B-field strength using exact Compton scattering cross section. The influence of the resonant scattering and photon polarization was taken into account for the first time. It was shown that the critical luminosity is not a monotonic function of the

NS magnetic field strength. It reaches a minimum of a few 10^{36} erg s^{-1} when the corresponding cyclotron energy is about 10 keV. For small field strengths, this luminosity is about 10^{37} erg s^{-1} and nearly independent of the parameters. The critical luminosity value grows for the B-field in excess of 10^{12} G because of the drop in the effective cross-section of interaction below the cyclotron energy. We have investigated how different types of the accretion flow and geometries of the accretion channel affect the results. It was demonstrated that the general behaviour of the critical luminosity on B-field is quite robust and that the obtained results are in a good agreement with the available observational data.

4.5 Paper V – A reflection model for the cyclotron lines in the spectra of X-Ray pulsars

In this paper we considered the cyclotron line behaviour in case of bright (super-critical) XRPs. At high luminosities, the cyclotron line variations were often associated with the onset and growth of the accretion column, which is believed to be the origin of the observed emission and of the cyclotron lines. We have shown that alternative scenario is that the absorption line forms when the accretion column radiation is reflected and reprocessed by the NS surface. In the paper we have developed a reflection model and successfully applied it to explain the observed variations of the cyclotron line energy in a bright XRP V 0332+53 over a wide range of luminosities.

4.6 Paper VI – Transient X-ray pulsar V0332+53: pulse phase-resolved spectroscopy and the reflection model

In this paper we presented the results of the pulse-phase- and luminosity-resolved spectroscopy of the transient XRP V 0332+53. It was done in a wide luminosity range $(1 \div 40) \times 10^{37}\,\mathrm{erg\,s^{-1}}$ for the first time. We have characterized the spectra quantitatively and built the detailed 'three-dimensional' picture of spectral variations with pulse phase and throughout the outburst. It was shown that all spectral parameters are strongly variable with the pulse phase. The observed phenomenology was qualitatively discussed in terms of the reflection model. As a result we have tested the reflection model and have made a step forward toward a new developing branch of observational analysis.

4.7 Paper VII – On the maximum accretion luminosity of magnetized neutron stars: connecting X-ray pulsars and ultraluminous X-ray sources

In this paper we studied properties of luminous XRPs using a simplified model of the accretion column obtained in the diffusion approach. Particularly, the maximally possible luminosity was calculated as a function of the NSs magnetic field and spin period. It was shown that luminosity can reach values of the order of $10^{40}\,\mathrm{erg\ s^{-1}}$ and even higher, but only for magnetar-like magnetic fields ($B > 10^{14}\,\mathrm{G}$) and long spin periods ($P > 1.5\,\mathrm{sec}$). This work explains the recent discovery of a NS as a compact object in ULX M82 X-2. The relative narrowness of an area of feasible NSs parameters which are able to provide higher luminosities leads to the conclusion that $L \simeq 10^{40}\,\mathrm{erg\ s^{-1}}$ is a good estimate for the limiting accretion luminosity of neutron stars. From the facts that this value (i) can be reached by accretion onto the neutron stars, and (ii) coincides with the cut-off value observed in the HMXBs luminosity function, and that (iii) HMXBs luminosity function does not show any features at lower luminosities, we have made conclusion that a substantial part of ULXs are accreting neutron stars in binary systems.

4.8 Paper VIII – Propeller effect in action in the ultraluminous accreting magnetar M82 X-2

No magnetars up to date have been seen in binary systems. In this paper we have shown that the ULX M82 X-2 regularly enters the propeller regime of accretion which is seen as dramatic variations of the emitted luminosity and two well defined peaks in the X-ray luminosity function separated by a factor of 40. These observations imply the dipole component of the neutron star magnetic field to be $\sim 10^{14}\,\mathrm{G}$, making the source the first accreting magnetar. With this paper we have also confirmed the result of the Paper VII where we have predicted the same field strength for NS in ULX M82 X-2.

4.9 The author's contribution to the thesis

In Paper I the author of the thesis independently made all analytical calculations, adapted the theoretical formalism for the calculation scheme, prepared the code and the manuscript.

In Paper II most of the analytical calculations were done by author of the thesis. The author has prepared the manuscript.

In Paper III the author proposed the idea for the phenomenon observed in sub-critical X-ray pulsars, made the numerical modeling and prepared the manuscript.

In Paper IV the author of the thesis together with V. Suleimanov prepared the theoretical background for careful calculations of critical luminosity value as a function of magnetic field strength. The author has included the magnetic scattering cross-section into numerical model, written the code and prepared most of the manuscript.

In Paper V the author participated in the development of the theoretical base of the paper, has proposed the idea of explanation of the absorption line formation after reflection of column radiation from the neutron star atmosphere. The author also independently made numerical calculations and participated in manuscript preparation.

In Paper VI the author of the thesis has taken part in the discussion of theoretical explanation of the obtained observational results.

In Paper VII the author developed the analytical base for a simplified model of the accretion column in diffusion approximation, has prepared the code, discussed the obtained results with co-authors and prepared most of the manuscript.

In Paper VIII the author participated in development of the main idea of the paper, contributed to the discussion of the obtained observational results.

Chapter 5

Main results and outlook

5.1 Results

We have constructed an useful calculation framework to obtain accurate Compton scattering cross-section in strong magnetic fields. Our framework has been developed for the most general case. Photon polarization, electron spin state, accurate Landau levels width have been taken into account. It makes our scheme quite useful for the solution of number of astrophysical problems. We used our framework in studies of accretion onto highly magnetized NSs, which are observed as X-ray pulsars.

We have analysed carefully the process of formation of cyclotron line absorption features in the spectra of XRPs. The general conceptions were revised both for sub-critical XRPs, with hot spots on their surface, and bright XRPs, in which the accretion column arises above the stellar surface. Since the analysis of the cyclotron line behaviour is an important method of diagnostic for accreting NSs, the revised conceptions and new models, which were proposed in our papers can play a key role in further understanding of this type of objects.

Using the carefully calculated scattering cross-sections we were able to find the correct radiation pressure in case of strong magnetic fields. With this knowledge we have analysed the main features of the dynamics of the accretion process onto magnetized NSs and found two luminosity values of particular interest. They are the critical luminosity value, where the accretion flow is stopped by radiation pressure above the stellar surface and an accretion column begins to grow, and the maximum accretion luminosity, which limits the stable accretion onto magnetized NS. Both these luminosities were calculated as functions of the NS surface magnetic field strength. The results on the critical luminosity value are waiting for observational tests, which can come any day now with the currently operating space observatories *NuSTAR* and *INTEGRAL*. The results on the maximum luminosity value can explain the phenomenon of ULXs as accreating highly magnetized NSs ($B \gtrsim 10^{14}\,\mathrm{G}$) and called into question the suggestion that most of ULXs are accreting black holes.

The peculiar nature of ULX M82 X-2 as an "accreting magnetar" was confirmed independently, which is also a result of the current work.

5.2 Future studies

A few projects are originating from the results and discoveries obtained in my doctoral studies. These projects can be divided into three groups.

5.2.1 X-ray pulsars

It would be interesting and relevant to construct accurate self-consistent models of accretion flow breaking near the NS surface including hydrodynamics and radiation transfer. This could be done both for sub-critical and super-critical sources. These calculations will improve largely our knowledge about the beam pattern and cyclotron line formation. That is quite important since nowadays we are able to get precise data, including phase resolved information, using as an example the *NuSTAR* space observatory.

In order to develop the models of super-critical XRPs, where accretion columns are formed, it is necessary to construct an accurate numerical model of cyclotron line formations due to reflection of column radiation from the NS atmosphere. Though the reflection input to the bright spectra was proposed by Lyubarskii and Syunyaev (1988); Poutanen et al. (2013) and confirmed by Lutovinov et al. (2015) and by Postnov et al. (2015), a more accurate analysis is still needed.

Another possibility for further work in this field is connected with an extension of the already obtained results to the non-stationary, time dependent case. Most processes are considered as stationary and their time dependence has been beyond any theoretical investigation reachable so far. However, the possibility of non-stationary processes was discussed with reference to XRPs (see Basko and Sunyaev 1976; Revnivtsev et al. 2015) and it is believed that some non-stationary processes might take place, when the NS reaches its maximum accretion luminosity value (Mushtukov et al., 2015a). It would be important to develop this field since in visible future the observatories like the Large Observatory for X-ray Timing, *LOFT*, focused exactly on studies of X-ray sources time variability (see Orlandini et al. 2015; Feroci et al. 2014), could be developed.

Another project is connected with the unique transient bursting X-ray pulsar GRO J1744–28 (Kouveliotou et al., 1996), which is probably the first and only known XRP, which has been suggested to show Type I (nuclear) bursts (Doroshenko et al., 2015a). The surface magnetic field of this pulsar was recently found to be $\sim 4 \times 10^{11}$ G (D'Aì et al., 2015; Doroshenko et al., 2015a), and it is interesting that the maximum luminosity of the pulsar during its outbursts is close to the maximum possible accretion luminosity for its measured magnetic field strength (Mushtukov et al., 2015a). In this sense it would be important to apply recently proposed model of the accretion column to GRO J1744–28 and see how it can explain the observed activity.

5.2.2 ULXs as accreting NSs

It was found that part of ULXs are accreting NSs (Bachetti et al., 2014) with extremely high surface magnetic field (Mushtukov et al., 2015a; Tsygankov et al., 2015). It is known that the accreting NS reaches the equilibrium within a few hundreds years in this case (Lipunov, 1982). Therefore one can expect that a substitutional fraction of ULXs would show long-term variability of luminosity with bimodal distribution of its value (see Tsygankov et al. 2015). In this sense it is relevant to search for this kind of ULX variability, which would be a good method of detection of highly magnetized NS in ULXs.

5.2.3 Contribution to the NS atmosphere models

Compton scattering cross-sections and redistribution functions obtained for the case of strong magnetic field can be adopted and applied widely for the studies of atmospheres of magnetized NS, where resonant Compton scattering is not taken into account so far (Potekhin, 2014).

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