5.3 Stellar mass compact objects

5.3.1 Galactic sources

Galactic compact X-ray sources contain a white dwarf star, a neutron star or a stellar mass black hole. They form a heterogeneous class of X-ray emitters, that may be powered by accretion, eruption, magnetic field decay, stellar spin-down, collapse, remnant heat and other less common mechanisms. Galactic compact X-ray emitters hold the key to understand evolutionary channels both of single and binary stars. As individuals they offer incredible diagnostic power via timing and spectroscopy; as a class, they provide key information on population synthesis models and are essential to unveil the nature of the diffuse Galactic Ridge X-ray Emission (GRXE) observed in the Milky Way and in other galaxies.

The scientific impact of the *eROSITA* survey in the field of compact objects in our (and nearby galaxies) is governed by two factors: (1) its discovery potential and (2) its monitoring potential via multiple observations. The discovery power lies in the *eROSITA* ability to detect many new point-like X-ray source identifying Galactic compact candidates (or compact objects in the Magellanic Clouds) among them. The latter is a very challenging task which will in most cases require follow-up X-ray or multi-wavelength observations (see Chapter 6). However, a number of identifications will already be possible on the basis of the *eROSITA* data alone, thanks to the instrument's spectral (up to several keV) and timing resolution which were very limited in previous all-sky X-ray surveys.

The monitoring potential of *eROSITA* is related to the observational strategy during the survey, which allows multiple observations of a considerable portion of the sky around ecliptic poles. Many X-ray sources located in those regions will therefore be repeatedly observed with an “XMM-class” instrument for the first time, which will allow an unprecedented study of their long-term flux, spectral and timing variability. The following paragraphs describe the objectives of the *eROSITA* mission per source class, beginning with the single compact objects followed by the more abundant accreting binaries; within those main classes ordering is done according to gravity.

5.3.2 Isolated systems

A. Isolated White Dwarfs: The final phase of evolution of low and intermediate mass stars begins with their departure from the AGB. They evolve at almost constant luminosity towards extremely high effective temperatures ($T_{eff} > 10^5$ K) while they are burning H or He in shells. When their nuclear burning finally ceases, the stars begin to fade and cool and enter the hot end of the white dwarf cooling sequence. Thermal soft X-ray emission is detected from many hot hydrogen-rich white dwarfs (spectral type DA) with an effective temperature in excess of $T_{eff} \sim 20000$ K. The actual X-ray spectral shape of pre-white dwarfs and white dwarfs is very much dependent on the chemical composition of their atmospheres, which is enriched by radiative levitation of trace metals. All those objects have a relatively soft X-ray spectrum which can be modeled in great detail (e.g. Werner et al. 2004). They are thus invaluable for the calibration of spectrally resolving X-ray instruments. The hydrogen-rich DA-type white dwarfs HZ 43 A ($T_{eff} = 51100$ K) and Sirius B ($T_{eff} = 24900$ K) in particular were used to establish soft X-ray standards allowing inter-calibration between X-ray observatories (Beuermann et al. 2006) and will be used as ideal calibration targets for *eROSITA* as well.

B. Isolated Neutron Stars: The observed population of neutron stars is dominated by radio pulsars. In recent years, however, different subclasses of isolated neutron stars (INSs), characterized by peculiar properties and not yet understood physics, have been discovered: magnetars, thermally emitting INSs (a.k.a. the “Magnificent Seven”, M7, or XDINS), central compact objects in supernova remnants and rotating radio transients. While currently few of them are known, they might represent a considerable fraction of the neutron stars in the Galaxy. The few sources known are affecting already on our understanding of the

physics of matter at extreme conditions of gravity and magnetic field. Understanding evolutionary relations between different subgroups and establishing a comprehensive picture of neutron stars birth and evolution in the Milky Way requires larger sample than known today. Highly sensitive optical surveys (such as SDSS, VISTA, etc.) coupled to the 30-fold increase of the *eROSITA* sensitivity with respect to *ROSAT*, will enable the mission to discover and identify many new members in the classes of INS. While multi-wavelength follow up of several candidates will still be crucial, as a matter of fact magnetars (AXPs, SGRs), CCOs, M7-like and young X-ray bright pulsars all have very faint optical companions which are difficult to identify: the timing and spectral capabilities of *eROSITA* come as a valuable addition in the identification process. In particular, XDINS constitute a homogeneous group of seven nearby, cooling, middle-aged INSs discovered by *ROSAT*, which display unique properties. Their proximity and the combination of strong thermal radiation and absence of significant magnetospheric activity make them ideal targets for testing NS atmosphere models, deriving radii and constraining the equation of state of neutron star interior. It is remarkable that a group of very similar sources, displaying at the same time unique properties that are so different from ordinary radio pulsars, are all detected in the very local Solar vicinity. Is this fact an anomaly caused by the Sun's current location near regions of active star formation of the Gould Belt or is it really signaling that radio surveys do miss a large population of INSs, at least as large as that of standard radio pulsars? Answering these questions will be possible with the unprecedented survey efficiency of *eROSITA*. It will allow the detection of more than 100 new X-ray thermally emitting INSs thus increasing the population by an order of magnitude (Pires et al. 2011). A major statistical and observational challenge will be the identification of the new XDINS in suitably tailored optical follow-up programs. Before *ROSAT*, predictions were made to discover thousands of isolated neutron stars reheated by accretion from the interstellar medium (e.g. Treves & Colpi 1991; Blaes & Madau 1993) but none were found. The much larger sensitivity of *eROSITA* will shed new light on the Bondi accretion efficiency and the NS velocity distribution

C. Isolated Black Holes:

Stellar-mass black holes have so far only been identified in binary systems. However, stellar-population-synthesis models and chemical enrichment models indicate that also a large number of isolated stellar-mass black holes $10^{8..9}$ should reside in the Galaxy. These sources could in principle be detected through their X-ray emission arising from Bondi-Hoyle accretion from the interstellar medium. Rate predictions for *eROSITA* depend on a large number of uncertain input parameters. While black holes should be less common than isolated neutron stars, their higher masses and on average lower space velocities should lead to $\sim 10^3$ times higher Bondi-Hoyle accretion rates. However, due to the lack of a hard surface, the accretion on a black hole should have significantly less efficiency than accretion on a neutron star. Depending on the exact value of the efficiency (could be between 10^{-2} to 10^{-4}, detections of isolated black holes may be more or less frequent than detections of isolated neutron stars (Algol & Kamionkowski 2002)

Most isolated black holes should be persistent accretors and predominantly located in high-density regions such as molecular clouds. This complicates the distinction from e.g., X-ray emitting hot corona of massive stars. *eROSITA*'s spectral coverage and time capability will be important to identify these systems.

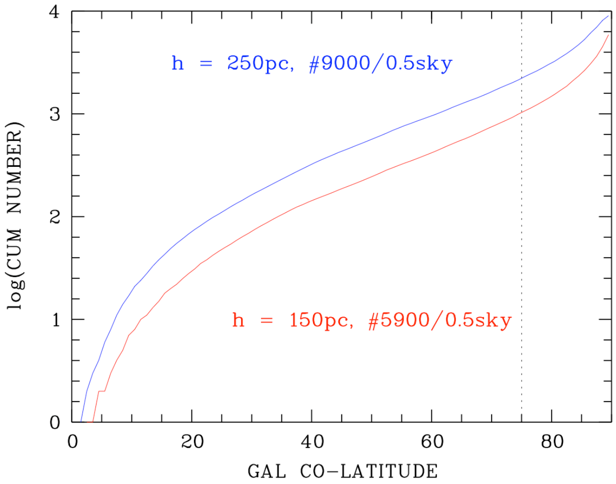
5.3.3 Binary systems

Most of the X-ray compact objects are found in accreting binaries, in which a compact companion (a white dwarf, a neutron star or a BH) accretes matter from a primary star. In High mass X-ray binaries (HMXRBs), the primary star is a massive ($M>10\ M_{\odot}$) Be or Oe star characterized by a variable disk-like envelope along ist rotational equatorial plane. In Low Mass X-ray Binaries (LMXRBs) plasma from a later than type A star ($M < 1\ M_{\odot}$) or a white dwarf, is accreted onto a compact companion. In all these systems the compact object accretes matter from the secondary star, either via an accretion disk or an accretion stream/curtain fed by Roche-lobe overflow, via a stellar wind or via rapid thermal-timescale mass transfer.

A. Cataclysmic variables: Cataclysmic variables are binary systems containing either magnetic or non-magnetic white dwarfs (CVs and MCVs). Some subclass is expected to contain the long-sought progenitor of the Supernova type Ia explosions, candidates being the double degenerates (DD, Schaefer & Pagnotta 2012), the Recurrent Novae (RN), the hard X-ray emitting Symbiotic Binaries (Kennea et al. 2009), and the Supersoft X-ray Sources (SSS).

Although almost 1000 CVs are known, we are far from establishing a coherent picture about their evolutionary role and their contribution to the X-ray active Milky Way. Main reasons are the highly biased sample composition and the uncertainties in the distance estimates. Cataclysmic binaries were detected in various ways, due to their strong variability, their blue color or due to pronounced soft X-ray emission, and each method left largely unknown imprint on the observed population. Complete samples that were used to determine space density comprise typically one or two dozen of objects and estimated space densities vary by up to two orders of magnitude (Hertz et al. 1994, Schwope et al. 2002, Pretorius et al. 2007, Pretorius & Knigge 2011).

The situation will substantially change since the *eROSITA* survey will unravel the zoo of compact binaries for the first time within ~1kpc radius down to a luminosity of 10^{30} erg s^{-1}, the minimum luminosity of CVs in the ROSAT Bright Survey (RBS, Schwope et al. 2002) and the *ROSAT* NEP (North Ecliptic Pole survey, Pretorius et al. 2007). Assuming the most up to date luminosity function of non-magnetic CVs (Pretorius & Knigge 2011) one may expect a cumulative number of CVs as a function of the Galactic co-latitude as shown in the figure for scale heights of 150 pc and 250 pc, respectively, representing a moderately young and old population. In the calculation a mid-plane space density $\rho_0 = 0.6\text{x}10^{-5}$ pc^{-3} was assumed, which is uncertain by a factor of two or more. Hence, *eROSITA* is expected to detect several thousands non-magnetic CVs in a flux-limited sample with radius 900 pc. On the other hand, predictions were made that the mid-plane space density of CVs might be as high as $2\text{x}10^{-4}$ pc^{-3} (Kolb 1993). Should such a population exist, it would have luminosities below $2\text{x}10^{29}$ erg s^{-1} (Pretorius et al. 2007) and about 5000 of those low luminosity sources would populate the *eROSITA* X-ray sky.



CAPTION: Cumulative number counts as a function of Galactic zenithal distance of non-magnetic CVs predicted in each *eROSITA* hemisphere based on a luminosity function of *ROSAT*-detected CVs (Pretorius & Knigge 2011).

Most CVs will be discovered in the soft band between 0.5 and 2 keV. Recent surveys at higher energies with *Swift*, *INTEGRAL*, and *RXTE* have revealed a significant number of magnetic CVs (Intermediate Polars and asynchronous Polars) that might be sufficiently abundant to synthesize the Galactic Ridge X-ray Emission (GRXE). Adopting a minimum IP luminosity in the 2-10 keV band of 10^{32} erg s^{-1} and a 10% IP fraction among the CVs, *eROSITA* will yield a flux-limited IP sample with radius 1.7 kpc that contains 9000 IPs. Hence, the whole eROSITA sky will contain tens of thousands CVs of all flavours.
Distance determination with Gaia and optical identification with spectroscopic facilities are essential to proceed further. With this unique data set one can:

(i) Uncover the parent population of CVs free of selection and detection bias from flux-limited samples comprising about 10^3 objects. For the first time the true composition of the CV population with magnetic and non-magnetic systems will be uncovered to constrain the effect of magnetic fields on close binary evolution;
(ii) Probe the existence of the putative large population of low-luminosity CVs with $L_X=10^{29}$ erg s^{-1}, predicted by binary population synthesis, and determine their local CV space density with 10% accuracy or better. This number will have a big impact on theoretical models of close binary evolution (strength of angular momentum loss) and on CV birth rates;
(iii) Measure the galactic scale height and luminosity functions of both magnetic and non-magnetic CVs. The population parameters will be determined in a local volume to synthesize the galactic ridge X-ray emission with high fidelity. We will finally solve the decades lasting debate about the true nature and composition of the GRXE by extrapolating from the local sample into the Milky Way. The CV surveys will definitely uncover rare objects of great importance for astronomy and fundamental physics. Examples are the hard X-ray emitting Symbiotic Binaries, the Double Degenerates and the Galactic SuperSoft X-ray sources, all of them being regarded as SNIa progenitor candidates.

Double Degenerates (or AM CVn stars) exist in ultra-compact configurations with orbita periods ranging from 65 min down to 5.4 min (see Solheim 2010 for a recent review). They are important laboratories for binary stellar evolution theory, in particular to elucidate the elusive common-envelope phase, and can potentially produce rare, sub-luminous, SNIa-like explosions (e.g. Bildsten et al. 2007, Nelemans et al.

2001, Podsiadlowski et al. 2003). They are the strongest known sources predicted to emit gravitational waves that can be detected with future space-based Laser Interferometers (e.g. LISA or NGO; see Nelemans et al. 2004, Stroeer et al. 2005, Roelofs et al. 2007). Although 10^4 to 10^5 systems are predicted to be in the Milky Way (Nelemans et al. 2004, Roelofs et al. 2007), only 27 have been discovered so far. Of those, nine have been detected as soft X-ray emitters with unabsorbed fluxes of $\sim 10^{-13..-14}$ erg cm^{-2} s^{-1} corresponding to luminosities of $\sim 10^{30..33}$ erg s^{-1}. If those numbers can be regarded as typical and assuming the recently estimated space density of about (1-3) x 10^{-6} pc^{-3}, *eROSITA* is expected to uncover roughly 1300 Double Degenerates.

Supersoft X-ray sources (SSS) are featuring steady hydrogen shell burning on the surface of a massive white dwarf. Together with the recurrent novae they are promising candidate progenitors for Type Ia supernovae via the single degenerate channel. The small population of currently known SSS is very inhomogeneous and heavily biased towards unabsorbed, high luminosity sources, which do not undergo temporal variations. This is partially reflected in the disjunct SSS samples found in the Milky Way, the Magellanic Clouds and M31 (4, 15 and 90 sources, respectively, Orio et al. 2010), with the M31 census strongly contaminated by classical novae undergoing a supersoft phase after the thermonuclear runaway. Assuming that the known sources are representative of the entire population, it appears that the initial theoretical expectations of ~1000 sources per galaxy (di Stefano & Rappaport 1994) are highly overestimated, a finding which is partially confirmed by the deficiency of integrated soft X-ray flux from several elliptical galaxies (Gilfanov & Bogdan 2010). There is however the possibility that a large fraction of SSS is predominantly in a state where the high energy flux is shifted into the unobservable UV (as observed in the transient sources CAL 83 or RXJ0513.9-695), or hidden by absorbing interstellar material. *eROSITA* has the great potential of uncovering such hidden population in our galaxy by detecting X-rays not from the shell burning white dwarf, but from the accretion process itself.

B. Galactic Novae in the *eROSITA* all-sky survey: The outbursts of classical novae (CNe) are caused by the explosive hydrogen burning on the WDs hosted in CVs. After sufficient H-rich material is transferred to the WD, ignition in degenerate conditions takes place in the accreted envelope and a thermonuclear runaway is initiated. As a consequence, the envelope expands and causes the brightness of the star to increase to maximum luminosities up to 10^5 $L_\odot$. A fraction of the envelope is ejected, while a part of it remains in steady nuclear burning on the WD surface. This powers a bright supersoft X-ray source (SSS) radiating at about the Eddington limit which can be observed as soon as the expanding ejected envelope becomes optically thin to soft X-rays (Gallagher & Starrfield 1978). The duration of the SSS phase is inversely related to the WD mass while the turn-on of the SSS is determined by the mass ejected in the outburst. The SSS phase can last from less than a month to more than ten years (Pietsch et al. 2007). In addition shocks may form in the ejecta giving rise to a lower luminosity hard X-ray source (V382 Vel, Orio et al. 2001). Henze et al. (2011) derived correlations between several optical, X-ray and physical parameters of a sample of novae in M 31.

In the Galaxy, to date about eight novae are detected every year (Pietsch 2010). Most of these novae have been followed up in X-rays with the help of monitoring campaigns with the *Swift* satellite (Ness et al. 2007) and also with *Chandra* and *XMM-Newton* observations. They showed a diversity of time variability patterns and partly complicated variable spectra with emission and absorption lines.

During its four year all sky survey, *eROSITA* will allow us to get a homogeneous census of the X-ray behavior of all Galactic (and Magellanic Cloud) novae with snapshots every half a year. While we may miss novae with a short SSS phase, we will efficiently follow the development of novae with long SSS phases. We will be able to investigate X-ray spectra and light curves and also trigger follow-up X-ray monitoring campaigns with shorter observation intervals and/or observations with X-ray instruments providing higher spectral resolution. During the survey we also may detect SSS from novae where the outburst has been missed in optical observations. This was the case for XMMU J115113.3-623730, which was detected during an *XMM-Newton* slew maneuver and later identified as a nova (see Greiner et al. 2010). Detailed modeling will allow us to constrain the number of novae showing a SSS phase and to extend correlations between nova parameters and compare them to those derived for M 31.

C. X-ray binaries in the Milky Way: Over 300 Galactic XRBs are known (114 HMXBs and 187 LMXBs, over 100 of them are X-ray pulsars; Liu et al. 2006, 2007), and yet this may be just the tip of an iceberg. They exhibit amazing diversity of properties, often variable on timescales ranging from ms to years. Many XRBs are heavily absorbed, which makes it difficult to detect and identify them in existing soft X-ray surveys. As a matter of fact, the Galactic XRB luminosity function in the 2-10 keV energy range is poorly constrained for fluxes below 10^{-10} erg s^{-1}, while the majority of sources are expected to be fainter (Grimm et al. 2002). On the other hand, many objects are dim/soft enough to escape existing hard X-ray surveys. e*ROSITA* is expected to improve in sensitivity in the 2-10 keV energy range by a factor of ~10^3, and to exceed by far the sensitivity of existing hard X-ray all sky surveys (about 4 x 10^{-12} erg s^{-1} for *INTEGRAL*, Krivonos et al. 2010).

From the observed luminosity function and current population synthesis studies one might expect about 3000 new XRBs (mostly LMXBs) to emerge from the *eROSITA* survey (Grimm et al. 2002; Belczynski et al. 2004). And in fact this population already started to emerge in pointed observations with *Chandra* (Muno et al. 2006). *eROSITA* will provide a complete census of the Galactic population of the accretion powered X-ray binaries down to luminosities of about $10^{33..34}$ erg s^{-1}. Many fainter sources as well as new transient sources will be discovered not only in the Galaxy but also in the LMC and the SMC. The *eROSITA* survey will provide a robust estimate of the galactic XRB X-ray luminosity function and provide constraints for population synthesis models. This will help to understand the origin and evolution of X-ray binaries in the Galaxy.

In addition, properties of known nearby transients in quiescence will be probed. *eROSITA* will monitor state transitions in known LMXBs and observe many thermonuclear bursts with high time resolution (several per each of the almost 50 known bursters). These observations, as discussed by Poutanen et al. (2010) and Duncan et al. (2008), will most likely provide new constraints on the equation of state of neutron stars.

New high-quality data taken with *RXTE, INTEGRAL*, and *Suzaku* on a number of transient and persistent X-ray pulsars allowed a detailed study of their spectral properties as a function of luminosity, i.e. of the mass accretion rate. The data reveal the existence of at least two different modes of spectral-flux dependencies, which are most probably due to different accretion regimes realized in different sources depending on the averaged accretion rate (Klochkov et al. 2011). The emerging diversity of the accretion modes, which is of key importance for understanding of the physics and configuration of the accretion flow close to the neutron star surface is currently studied on a relatively small sample of X-ray pulsars. The monitoring capability of *eROSITA* will allow to extend this analysis to a larger sample of sources by measuring the slope of the X-ray continuum at different luminosity states of transient sources. The Liu et al. (2006) catalog of XRB contains 28 transient accreting pulsars which will be included in the sample using *eROSITA* data.

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