"Per aspera ad astra..."

Contents

CHAPTER 1

Introduction to the stars in high energy

Let your imagination soar. By sitting on the old rocker looking at the sky with couple of good old whiskey you can easily start thinking about the universe. You are looking at a heck of a different kinds of cosmic objects, but suddenly you see almost only the stars. Almost all the shiny dots on the sky are stars and these stars are only the closest ones. Yes, you can see few other galaxies by naked eye[1], but none of the exotic cosmic objects you are imaging about. They are too faint to be observed easily, because they are not only far, far away, but they also usually shine on different wavelengths, not visible by human eye.

Think about distances in the universe. One of the most accurate explanation is that from: Adams (1979) *”Space,” it says, ”is big. Really big. You just won’t believe how vastly, hugely, mindbogglingly big it is. I mean, you may think it’s a long way down the road to the chemist’s, but that’s just peanuts to space...”*

Consider this, sometimes you want to study processes in these extreme, very faint objects, but they are too faint and too far in the universe. You are looking for “laboratory” with similar processes, but located much closer to the observer. The X-ray binary stars can be this kind of laboratories.

There is, of course, many interesting phenomena which could be studied in X-ray binaries or in non-binary X-ray stars. Several of them are mentioned in the motivation section.

I am mentioning many interesting things in this work, but the main effort is taken to study post shock region in the Intermediate Polars (IPs).

[1]M31 and M33 in extremely good conditions on northern hemisphere and Magellanic clouds on southern one

1.1 Motivation

We can easily find many reasons why to study stars in the high energy bands. We can consider the direct and the most common scientific applications like observations of the supernovae, black holes & neutron stars in X-ray binaries. But for the education purposes I prefer several others, very nice examples closer to topic of this work.

- **Relativistic jet phenomena**: like it was proposed by Mirabel (2002) that universal mechanism should be at work in all the relativistic jet sources in the universe. Better understanding of sources including: microblazars, AGNs and gamma-ray burst will help to gain more comprehensive understanding of these phenomena. Microblazars can play role of "space laboratories", where interesting processes last on different timescales as is the case with AGNs or GRBs.

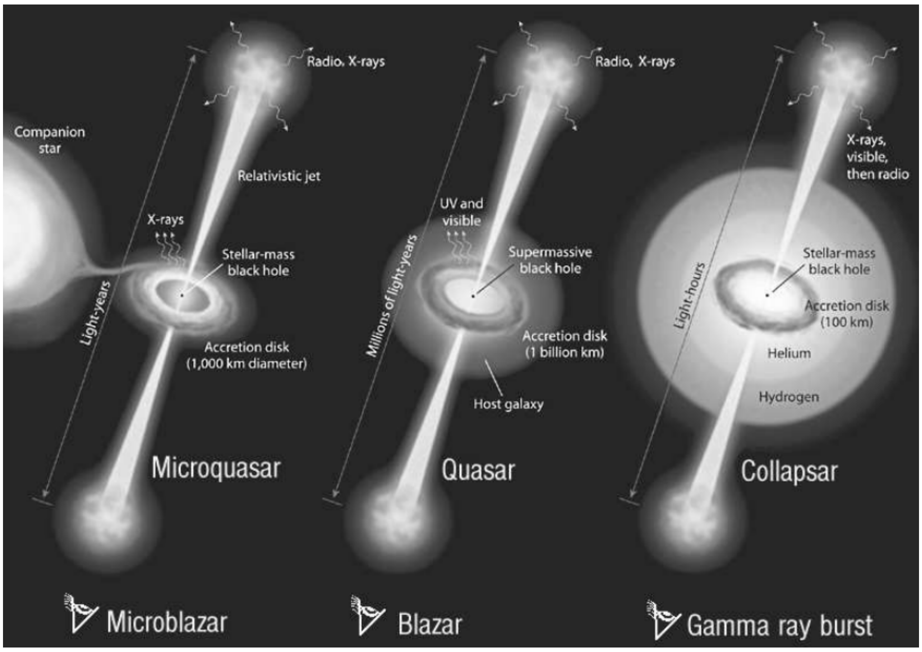

Figure 1.1: NOT in scale diagram, showing curent ideas of micro-quasars, AGNs and gamma-ray bursts as space objects driven by same, universal mechanism Mirabel (2002).

- **Galactic ridge X-ray emission (GRXE)**: various physical processes contribute to brightness of GRXE in different bands, but several studies in 3-20 keV provide evidence that diffuse X-ray radiation originates from huge number of stellar X-ray sources, mostly coronally active stars and white dwarf X-ray binaries. In particular for the energies over 20 keV to 200 keV is spectrum very similar to spectrum of magnetic white dwarf binaries – e.g. Intermediate polars (IP) and polars (P). Krivonos et al. (2007)

- **White dwarfs masses in Intermediate Polars (IP)**: as was proposed in Rothschild et al. (1981), the temperature of the post shock region (PSR) depends on WD mass. Therefor the X-ray spectrum can be used for WD mass determination Suleimanov et al. (2005). The WD mass estimations in cataclysmic stars is in general complicated. Usually the curve of radiation velocities can be used, but it is quit hard to constuct and because of . Therefor X-ray spectrum method is very atractive for several reasons. This work is dedicated to this topic.

1.2 Aim of this work

To cover the whole topic: "stars in high energies" is far behind capacity of such master thesis, because of that I decide to aim on cataclysmic variable stars (CVs), especialy to intermediate polars (IPs).

As it will be mentioned in next sections closely, IPs are magnetized CVs where the compact, primary star is white dwarf with $B \sim 10^6 - 10^7$ Gauss. The mass accretion is taking place from, mainly low-mass, non-degenerate star through Roche lobe. Accretion disk is in some distance from WD surface destroyed by strong magnetic field and accretion continuous through, so called, accretion curtain across magnetic force-field.

Falling material in some point creates stationary shock near the WD surface where the kinetic energy is converted through thermal bremsstrahlung to radiation. The temperature of such created plasma is typically more than 10 keV with low density. The optically thin hard X-ray[2] emission is taking place and heated gas creates post shock region (PSR) with temperature gradient. The hot gas then descends and cools by X-ray emission while it hits the WD surface.

Because of relatively high temperature of PSR are IPs very good observed in hard X-rays band. IPs are only small fraction $\sim 15\%$ of all CVs, but they dominet in hard X-ray band over 10keV, ad most $\sim 80\%$ of detected CVs are IPsLandi et al. (2009).

The temperature of PSR depends in first order only on WD mass, which is the most fundamental parameter of WDs. This means, that if we are able to find temperature from fiting thermal bremsstrahlung model to spectrum of IP, we are also able to establis the WDs mass.

An accrating WDs are very important for cosmology, because some of such objects probably casuse Type Ia supernovae, when the WD mass reaches Chandrasekhar limit.

As is showed on figure 1.2, IP as NY Lup are well observed by INTEGRAL/IBIS detector which makes them iteresting space laboratories for WD basic parameters

[2]In this case, hard X-rays means 10 - 120 keV region.

study. In same casesm, can by also accretion stream studied if it is strong enough.

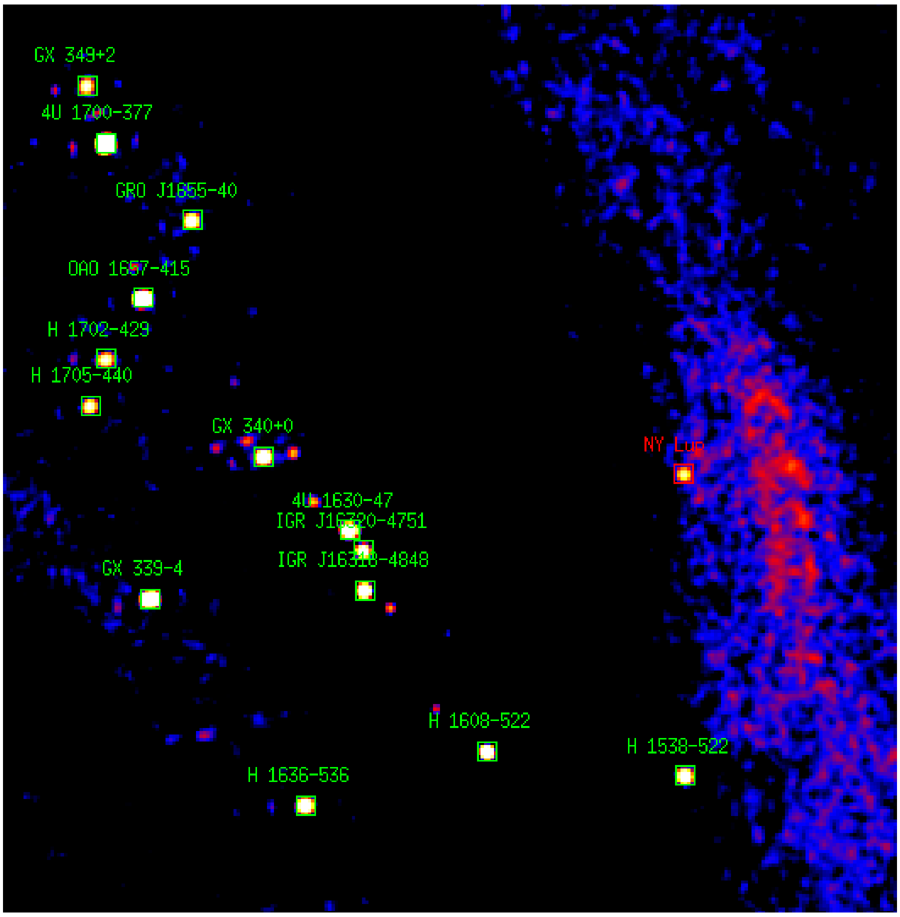

Figure 1.2: 1.2 Msec exposure of NY Lup region in 17-80 keV. The NY Lup is marked by red square. There are many others X-ray sources, mostly HMXBs or LMXBs which is because of .

1.3 Observations

Cataclysmic Variable stars (CVs) have been, in fact, observed as early as ancient times. In historical records of many civilizations we can find references for various astronomical events. Mostly they are about temporary objects: planets, Moon and Sun. However several are about comets and new stars. Rightly, these new stars are in many cases novae and supernovae. In China, the records date back to 1500 AD.

Many records are saved from medieval time, for example positions of *Nova Vulpecula 1670* and *Nova Cygni 1600* (now knows as P Cygni) in Hevelius maps.

With progress of astronomical photography in late 19th century started era of continuous observations and with development of first photo-multipliers in the mid-1940s CVs were begun attractive targets because of their big variability in different time scales.

It is suitable to mention, that AAVSO has light curve of SS Cyg from 1896 up to date.

1.3.1 Optical and IR observations

The very first visual observation was follows by photographic photometry and then spectroscopy, follows by photo-multiplier photometry since mid-1940s. The binary nature of all the CVs was confirm. The flickering was discovered and was assumed that it is somehow connected to stars duplicity Walker (1957), Warner (1995).

Statistical studies by Luyten and Hughes in mid-1960th showed, that novae remnants have $M_V \approx 4$ and dwarf novae at quisence have $M_V \approx 7.5$. They conculde that the hot primary star in CVs must by WD or hot subdwarf Warner (1995).

The most important contribution of optical astronomy to this work is the discovery of large and variable circular polarization in several CVs. This helped to identified magnetic CVs, which were later divided to two categories, polars and intermediate polars.

There are more important discoveries in optical and IR bands in CVs subject. In case of interest the Warner (1995) is proper book.

1.3.2 X-ray observations

The very first CV detected in X-rays was the EX Hya observed by Uhuru X-ray space mission. Uhuru works in 2.0 – 6.0 keV and in spite of its poor sensitivity the well-known 4U catalogue was created Forman et al. (1978) from its observations.

The NASA‘s HEAO[3] program follows with three space missions. As the X-ray detectors technology evolves, the number of detected CVs grown linearly. EXOSAT provided long and uninterrupted data of many CVs during his operation from May 1983 until April 1986. Similar results were obtained from Soviet mission Kvant 1 and Japan's Ginga. The high hopes were entered into ROSAT which provides all-sky survey in the 0.1 – 2.0 keV but expected huge number of new CVs was not discovered.

The situation slightly changes with RXTE[4] which after years on orbit provides good data for several articles about WD masses Suleimanov et al. (2005). The data from RXTE are used in new articles even ~ 15 years after its launch Butters et al. (2011).

Several others missions were launched in last ten years period. Few of them caried several detectors where one was sensitive in X-rays, like SUZAKU/XIS and Swift/XRT. But for the X-ray astronomy was been the year of 1999 the most important ever. The two major big observatories was launched on the Earth's orbit.

[3] High Energy Astronomy Observatory, The HEAO 2 was also known as The Einstein Observatory

[4] Rossi X-ray Timing Explorer

The Chandra X-ray Observatory onboard STS-93 space shuttle Columbia on July and the XMM-Newton launched onboard ESA's Ariane 5 rocket.

That was the beginning of the X-ray astronomy's golden era. During last decade the combination of Chandra and XMM provides enormous data archives which will be useful for astronomers for another decades.

Sadly, there will not be such big observatory in X-rays for several decades. Only bigger space mission is Japan's ASTRO-H with several X-ray and gamma ray detectors on-board to cover broad high energy bands. The future of big ESA & NASA space mission Athena (formerly: Constellation-X, XEUS, IXO) is questionable because of budget cuts in both space agencies.

Fortunately, there are several data archives with open data for anybody interested. This is big challenge mainly for young astronomers, who are not in any big space mission program but want to do science. In this case, they don't need any special hardware, even modern laptops are powerful enough.

1.3.3 Gamma ray observations

In last millennium several space mission observed few CVs in bands from tents of keV to TeV.[5] The biggest breakthrough came with ESA's INTEGRAL space mission which was able with its sensitivity and large field of view observed many CVs. Mostly intermediate polars. Only $\sim 2\%$ of all CVs are actually magnetic ones, but those ones are only visible in gamma rays. INTEGRAL/IBIS was been used to determine white dwarf masses by Landi et al. (2009).

Two others space missions have on-board detectors similar to INTEGRAL/IBIS with their sensitivity and coverage: the NASA's Swift/BAT and Japan's Suzaku/XRT. Both are widely used to study white dwarf masses in IPs Brunschweiger et al. (2009), Yuasa et al. (2010).

[5] The most studied CV from this era is AE Aqr (Meintjes 1990; Bowden et al. 1991)

CHAPTER 2

White Dwarfs

White dwarfs borns when normall mass stars die. WDs are degenerated, late type stars with typical mass ~ 1 solar mass. Their typical radius is about 5000 km and mean density around $10^6 g.cm^{-3}$ Shapiro & Teukolsky (2004). They no longer burn nuclear fuel and if they don't have any other mather influx e.g. like accretion from close star, they slowly cools as they radiate away residual thermal enegy.

WDs support themselves against gravity by the pressure of electron degenerate gas. The whole star is then in thermal equilibrium, except very thin atmosphere.

2.1 Inside of white dwarfs

WDs are a class of the less compact objects among the possible endpoints of the stellar evolution. The mass of the star is the main factor determining whether the star ends up as a WD, neutron star or a black hole. The medium mass stars with masses $M \lesssim 4M_{Sun}$ in some point of late state of their evolution gently spreads mass forming planetary nebulae. The rest of the star become the white dwarf.

Table 2.1: Basic statisticks of the compact objects

Object	Mass[a] $[M]$	Radius[b] $[R]$	Mean Density $[r.cm^{-3}]$	Surface Potential $[GM/Rc^2]$
Sun	$M_\odot$			
White Dwarf				
Neutron Star				
Black Hole				

[a]

[b]

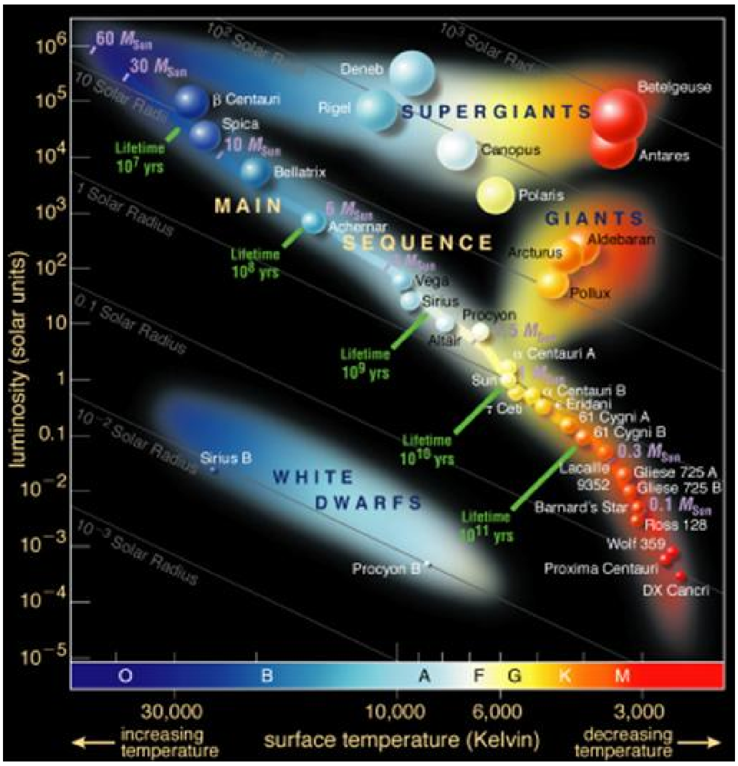

Figure 2.1: WD lies in right bottom corner of HD diagram, under main sequence, which exactly means, they are very small (dwarf) stars with high surface temperature.

2.2 The Chandrasekhar limit

CHAPTER 3

Cataclysmic variable stars

3.1 Non magnetic cataclysmic variables

3.2 Magnetic cataclysmic variables

3.2.1 Polars

3.2.2 Intermediate polars

3.3 Galactic population ofcataclysmic variables

3.4 Others important creatures

3.5 GXRE

CHAPTER 4

Masses of white dwarfs in intermediate polars

4.1 Breaking radiation

4.1.1 Bremsstrahlung

$$a_{\parallel} = \dot{v}_x = -\frac{eE_x}{m_e} \frac{\gamma {Z_e}^2 vt}{4\pi\varepsilon_0 m_e \left[b^2 + (\gamma vt)^2\right]^{2/3}} \tag{4.1}$$

4.1.2 Thermal bremsstrahlung

4.2 Synchrotron radiation

4.3 Post shock region

4.4 WD mass estimations methods

CHAPTER 5

Data analysis

5.1 INTEGRAL

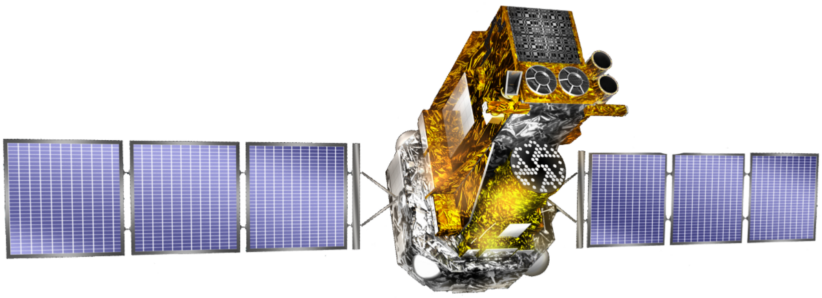

Figure 5.1: INTEGRAL

5.2 XMM-Newton

5.3 Results

5.4 Discussion

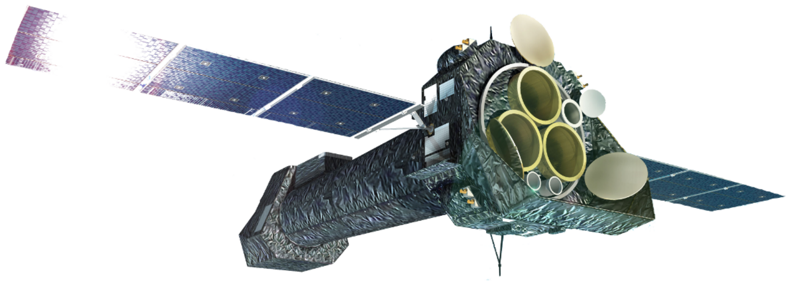

Figure 5.2: XMM-Newton

CHAPTER 6

Conclusions

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Appendix

this will be the appendix

Table 1: Estimated WD masses from previous reports ...

System	Suzaku	Swift	RXTE	RXTE	Ginga	ASCA	This work
	XIS+HXD	BAT	PCA+HEXTE	PCA	LAC	SIS	XMM & Integral
	M_{WD}	M_{WD}	M_{WD}	M_{WD}	M_{WD}	M_{WD}	M_{WD}
FO Aqr							
XY Ari							
MU Cam							
BG CMi							
V709 Cas							
TV Col							
TX Col							
YY Dra							
PQ Gem							
EX Hya							
NY Lup							
V2400 Oph							
AO Psc							
V1223 Sgr							
RX J2133							
IGR J17303							