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Hard X-ray and soft gamma ray properties of cosmic sources

Manojendu Choudhury*
National Centre for Radio AStrophysics, T.I.F.R., Pune-411007, India

Abstract. Microquasars provide a unique laboratory to study the accretion process in a compact object, coupled to the ejection of matter in the form of jets. In this thesis we provide a phenomenological perspective on the accretion-ejection mechanism based on the multi-wavelength observational features covering long term evolution of various sources exhibiting apparently diverse types of characteristics, with special emphasis on the enigmatic X-ray binary system Cygnus X-3.

Keywords : accretion – binaries : close – stars : individual (Cygnus X-3) – X-rays : binaries

1. Introduction

An X-ray is a quantum of electromagnetic radiation with an energy, to an order of magnitude approximation, some 1000 times greater than that of optical photons. Traditionally, the soft X-ray band is defined as the energy range 0.5 – 12 keV (corresponding to wavelength of 25 – 1 Å), the hard X-ray extends to $\sim$ 50 keV and the energy range beyond it till a few MeV is regarded as soft gamma rays, although this classification is not very stringent. High energy astronomy pertains to the observation of the sky in this regime of the electromagnetic spectrum. Simple extrapolation from the optical regime suggests that, assuming the physical processes giving rise to these X-ray, gamma ray emissions are thermal, the temperature of the radiating matter should be of the order $10^6 - 10^8$ K for X-ray photons and greater for gamma ray photons. The fundamental physical mechanisms which give rise to high energy emissions from a thermalised distribution of matter are few, viz. thermal black body radiation, bremsstrahlung, Compton scattering. Soon, however, it was discovered, mainly from the supernova remnants, that non-thermal

*e-mail:manojendu@ncra.tifr.res.in

physical processes also play very important part in these high energy emission. Such physical processes may also involve bremsstrahlung and Compton scattering, in addition to synchrotron emission.

This interplay of thermal/non-thermal emission is best observed in accreting black hole (both stellar mass and super massive) and neutron star systems. Various theoretical paradigms exist today which attempt to comprehensively explain the accretion phenomena in these systems. Shakura & Sunyaev laid the foundation of the first standard disc models (now known as SS discs). However these discs were untenable due to instability arising out of temperature crossing the hydrogen ionization point, and this led to the classic disc instability paradigm which sought to explain various transitions and variabilities in the accretion disc systems. Improved wide band X-ray observational capabilities enabled the spectral energy distribution (SED) of these sources to reveal the ubiquitous presence of power law component extending well into hard X-ray and gamma ray bands, along with any soft component (black body, generally multicoloured). Thereafter various paradigms involving hybrid (i.e. both thermal and non-thermal) Comptonization, advection dominated accretion flow (ADAF), Compton reflection, bulk motion Comptonization, two component accretion flows, etc., with or without magnetic field, were developed to explain the hard power law extension, the various states of black hole transitions and their variabilities. Models involving synchrotron emission, Compton self-synchrotron, etc., are also used to explain the high energy emission in these sources. Long term monitoring of the various high energy SEDs and variabilities of these sources are needed to devise any comprehensive physical and geometrical picture of the processes. The discovery of Galactic X-ray binaries exhibiting (superluminal) radio jets, with both physical and temporal (variability) scale roughly at 6 orders of magnitude less than those of quasars, led to the notion of ubiquitous presence of outflow in the form of collimated jets in accreting black hole systems and low magnetic field ($\leq 10^9$ G) neutron stars, lending them the terminology of microquasars. The observation of microquasars over the AGN is advantageous for, chiefly, two reasons. Firstly, these sources are located within the Galaxy, the astronomical equivalence of our own backyard. And, secondly, the characteristic dynamical time scales in the flow of matter are proportional to the black hole mass and any variability time scale of hours to days of microquasars correspond to analogous phenomena with duration of hundreds to thousands of years in AGNs, assuming that the same fundamental physical processes underlie the behaviour of these sources. Therefore monitoring the microquasars for a few days may sample phenomena not possible to observe in quasars. The aim of this thesis is to gather together a comprehensive picture of the high energy observational features of Galactic microquasars, with a particular emphasis on the enigmatic source Cygnus X-3 (whose X-ray spectral evolution is similar to that of black hole binary systems–(Choudhury & Rao, 2002) although the individual spectral model components are different from a canonical high-soft and low-hard state of stellar mass black hole candidates (characterized chiefly by Cygnus X-1), in order to develop a phenomenological understanding of the fundamental processes and geometrical structure of these systems. Since accretion and ejection are closely related, a correlated study of high energy and radio emission is presented to provide a coherent picture of the systems.

2. Disc: jet connection

In the last decade first efforts were made to create models to treat accretion and ejection in a unified scenario, underlying the physical connection between the two. Meanwhile, observational strategies were developed independently to monitor some of these sources in the radio and X-ray at a regular basis to study the long-term behavioural patterns in these systems, chiefly to observe the transient features of mostly transient and a few persistent sources. The most methodical and consistently regular of these strategies were the ones carried out in the radio at the Green Bank Interferometer (GBI) operated by NRAO, and concurrently in the soft and hard X-rays by All Sky Monitor aboard the Rossi X-ray Timing Experiment (RXTE - ASM, 2-12 keV) and the Burst and Transient Sources Experiment aboard the Compton Gamma Ray Observatory (CGRO - BATSE, 20-100 keV), respectively.

Our investigation commenced with the next logical step of understanding this connection at a broad scale across the diverse type of sources of this class exhibiting their characteristic idiosyncratic behaviour, in order to provide a unified, consistent set of observational features with the aim of developing a phenomenological model to unravel the physical and geometrical structure of these X-ray binary systems. We achieved this by carrying out a systematic correlation analysis among the radio, soft and hard X-rays, for the sources Cygnus X-3, GRS 1915+105 and Cygnus X-1, using the available data from the archives of GBI (2.2 & 8.3 GHz), RXTE-ASM (2-12 keV), CGRO-BATSE (20-100 keV), during the long term steady hard states of these systems. These three persistent X-ray as well as radio sources were the only ones monitored simultaneously by these three observatories. The results of the correlation studies from these sources was complemented by the observations reported for GX 339-4 (and also V404 Cyg), scattered in the literature, to provide a qualitative self-consistent picture of the disc-jet connection, using the Two Component Advection Flow (TCAF) model.In this thesis, our emphasis lies in the detailed multi-band (X-ray and radio) study of the enigmatic binary system Cygnus X-3, where we provide the complete evolution of the radio flaring episodes of Cygnus X-3 driven by the X-ray spectral states in the system. In addition, we report the temporal properties of the X-ray emission in this particular binary system and provide a time scale of anti-correlation between the soft and hard X-rays in the system. Of all the Galactic microquasars, Cygnus X-3 is one of the brightest in both radio and X-ray bands, but one of the least understood of all binary systems. The nature of the compact object of the binary system is still not conclusively ascertained, and a prime motive of undertaking the detailed X-ray spectral study was to glean the observational features that may pertain to any particular class of compact objects, black hole or neutron star. Detailed analyses of the X-ray spectra show a definite pivoting at about 12-20 keV in the hard state, correlated to the radio emission (Choudhury et al. 2002). In the soft state the picture is different with the thermal emission from the accretion becoming the prominent feature of the SED in most cases, with a definite causal relationship between the X-ray spectral evolution and the radio flaring events, which may be explained by stating that the huge flares are followed by the disappearance of the inner Compton cloud juxtaposed by periodic refilling of the same via the accretion flow. The succession of radio flares, both minor and major, are brought to an end by a change in the X-ray spectrum, with the spectral shape hardening and the thermal disc black body component vanishing (Choudhury & Rao 2004a). The short term temporal properties of the X-ray emission of Cygnus X-3 is perhaps the least studied aspect of this source. The power density spectra (PDS) of this source, obtained after correcting for the binary modulation, has a feature distinct from its counterparts, the shifting of the spectra towards low frequency (Choudhury et al., 2004). In this pattern of temporal variability it resembles less like other Galactic microquasars and bit more like the massive AGNs with a central massive black hole. One may reconcile the absence of power in the high frequency regime to the reprocessing of the X-ray photons in the dust and/or halo engulfing the system, reducing the amplitude of the fast X-ray variability. The most interesting result of the X-ray timing properties reported of the source, by us, is the anti-correlated time lag of 400–1000 seconds between the soft and hard X-rays in the low (hard) state of the system, signifying the presence of a truncated accretion disk (Choudhury & Rao 2004b).

The generalization of the X-ray:radio correlation, during the low (hard) state, for different types of microquasars, was done by repeating the correlation study of the long term radio, soft and hard X-ray monitoring data of two more sources with apparently diverse behavioural pattern, viz. GRS 1915+105 & Cygnus X-1, and collating the existing results of another black hole candidate GX 339-4 (Choudhury et al., 2003). It was successfully demonstrated that all these three sources, plus Cygnus X-3, show a very similar behaviour during the low (hard) state, i.e. pivoting of the X-ray spectra correlated to the radio emission, with the radio emission being higher in the comparative softer state (within the bounds of the hard state). The only difference lies in the pivoting energy of the individual sources. Most remarkably, all the sources (along with another black hole candidate, V404 Cygni), were found to show a linear monotonic increase of radio emission with the soft X-ray flux, spanning a 5 orders of magnitude variation in the intrinsic luminosities, with the radio emission suppressed for the intrinsically weaker X-ray emitters (during the non-flaring state). Therefore, for the first time, a uniform behavioural pattern was found of the radio emission and correlated X-ray spectral emission evolution, encompassing various microquasars with apparently different characteristics.

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