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X-RAY ASTRONOMY FROM SPACE

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The growth of X-ray astronomy since its beginning in 1962 is briefly discussed. Different types of X-ray sources are described and a detailed discussion of the characteristics of X-ray binaries is presented. Present international status of research in the studies of the X-ray binaries is summarized with special reference to the results from current satellite missions. Recent discovery of quasi-periodic oscillations with frequency in the range of about 500-1200Hz from several low mass X-ray binaries and their origin are discussed. Some of the important results from the X-ray spectroscopic observations with the ASCA satellite are highlighted. Indian research groups have contributed significantly to the temporal studies of X-ray binaries earlier with the balloon-borne instruments and now with the Indian X-ray Astronomy Experiment (IXAE) on the IRS-P3 satellite launched on March 21, 1996. Details of the IXAE are presented and important results obtained with it so far are described in some detail with reference to the black hole binary source Cyg X-1 and GRS 1915 + 105. The recent discovery of regular X-ray bursts with the IXAE from GRS 1915 + 105, which have the unique characteristics of slow rise and fast decay, is described in detail and it is shown that this is a possible indication of matter disappearing into the event horizon of the black hole.

Key Words: X-ray Astronomy; X-ray Binaries; X-ray Spectroscopy; X-ray Pulsars; Black Hole

Introduction

Before the advent of space age the astronomical observations were mainly limited to the 'visible' and 'radio' bands of the electromagnetic spectrum. The radiation in all the other wavebands is effectively absorbed by the atmosphere and therefore not accessible to the ground-based telescopes. This situation changed dramatically when it became possible to send instruments outside the earth's atmosphere in various kinds of space vehicles and space-based platforms like balloons, rockets, satellites and space probes. Many branches of 'Invisible' astronomy such as X-ray Astronomy, Ultraviolet Astronomy, Infrared Astronomy and Gamma-ray Astronomy opened up and it became possible to view the universe through these invisible windows by means of space-based observations.

Many astrophysical processes in the universe can be studied mainly through these invisible bands. Matter at very high temperatures ($\sim 10^5$ to 10^8 K), at very low temperatures (~ 10 to 500 K), very high energy particles (electrons of energy $>10^{15}$ eV), and a plasma in a high magnetic field environment ($\sim 10^7$ to 10^{13} Gauss) radiate predominantly in the invisible bands. The observations in these bands provide a glimpse of the radiation processes operating in the extreme conditions and reveal the nature of the sources in which the radiation originates. Stars being born or in their infancy as well as those near the end of their lives are also studied best through the invisible windows. Newly born stars in the giant molecular clouds have typical temperature of ~100K and radiate most of their energy in the far infrared region. The hot outer layers of the stars e.g., transition region and corona in the Sun and other hotter or cooler stars, have temperatures in the range of ($\sim 10^5$ to 10^7) K and radiate most of the energy in the extreme ultraviolet and X-ray bands. Matter found in the vicinity of neutron stars and black holes usually has temperature of 10^7 to 10^8 or higher and in several cases found in regions of high magnetic field. In such environment the matter is a prolific source of X-rays and low energy gamma-rays. At the end of their evolution the massive stars undergo violent and catastrophic explosions like supernova explosions. During the explosions, the core of the star collapses and forms either a neutron star or a black hole if the core mass exceeds $3M_\odot$. Remnants of these explosions i.e., supernovae remnants are powerful sources of radio, X-ray and gamma-ray radiation. The X-rays and gamma-rays emitted after the explosion serve as useful tools to probe the physical processes going on during and after the explosions.

Space based studies have resulted in the discovery of a host of new phenomena and objects. These include the existence of stellar mass black holes in X-ray binaries, massive black holes at the center of quasars and active galaxies, magnetized neutron stars with field $\sim 10^{12}$ to 10^{13} gauss, the puzzling mystery of Gamma-ray Bursts etc. Despite 25 years of intense efforts many of the phenomena are still not understood well.

Beginning and Growth of X-ray Astronomy

Since its beginning in 1962 with the chance discovery of the first extra-solar X-ray source Sco X-1, the X-ray astronomy has grown in a spectacular manner during the last 25 years and can now be regarded as the most developed among the space based astronomies. In the early years, the X-ray observations were mostly carried out with balloon and rocket-borne instruments. The launch of the first X-ray satellite UHURU in 1971 was a major milestone in the growth of X-ray astronomy. Immediately after its launch UHURU discovered binary X-ray stars with pulsating X-ray sources. These objects are believed to be powered by the release of gravitational energy by matter accreting from a companion star onto a compact object like a neutron star or in rare cases a black hole. This discovery marked a major advance into the understanding of astrophysics of these exotic objects. The first credible candidate for a black hole namely Cygnus X-1, was also first discovered in X-rays and later optically identified with a 5.6 day period binary HDE226868. In recent years many transient X-ray sources have been detected and about 15 of these, based on the estimate of the mass of the X-ray source and the X-ray characteristics, have been listed as strong candidates for black holes[1].

Almost all classes of celestial sources, both galactic as well as extragalactic, have been detected in X-rays. This includes the recent surprising discovery of X-rays from comet Hale-Bopp and other several comets. Most of the X-ray sources are rather faint and their detection has been made possible due to advances in X-ray imaging and detection techniques. Launch of the Einstein X-ray Observatory in 1978, which carried a grazing incidence reflecting X-ray telescope with X-ray imaging detectors at its focal plane, was the second major milestone in the development of X-ray astronomy. In the earlier missions, light collecting detectors like proportional counters and scintillation counters which had no imaging capability, were used. The use of X-ray imaging devices on the Einstein Observatory made it possible to obtain X-ray images of the sources for the first time and resulted in a quantum jump in X-ray resulted in a quantum jump in X-ray sensitivity by almost three orders of magnitude. This made it possible to detect X-rays originating from the distant originating from the distant quasars and galaxies as well as from stars of almost all spectral types in our galaxy. Indeed almost all categories of stars including the pre-main sequence stars, emit X-rays at some level. The X-ray emission from single and binary stars, excluding the binaries in which the X-ray source is either a white dwarf or a neutron star or a black hole, originate in the stellar coronae formed around the stars. The X-ray luminosity of the coronae is usually a very small fraction of the bolometric luminosity of the stars. This ranges from $\sim 10^{-3}$ for the chromospherically active stars like RS CVn binaries and dMe stars to about 10^{-7} for the early type O,B stars. Among the extragalactic objects the Active Galactic Nuclei (AGNs), a term which denotes bright and active nuclei of galaxies like Seyfert galaxies, quasars, BL Lac sources etc., are the most luminous sources of X-rays in the universe with luminosity in the range of 10^{44} to 10^{47} ergs per sec.

Different Types of Galactic X-ray Source

The first X-ray survey of the sky carried out with the UHURU satellite resulted in the detection of 339 sources listed in the 4U Catalog[2]. A majority of the sources in this catalog are galactic objects, mainly X-ray binaries, with some supernovae remnants. clusters of galaxies and a few AGNs. The next all sky survey with the HEAO A-1 experiment produced a catalog of 842 sources which included many coronal stellar sources as well as extragalactic objects[3]. The most recent sky survey was carried out with the X-ray imaging telescope in the 0.1-2 keV band with the ROSAT satellite and about 60,000 sources have been included in the first catalog. This number is likely to exceed 100,000 in the revised catalog. A majority of these sources are AGNs followed by stellar coronae in our galaxy.

X-ray binaries with a neutron star or a black hole as the X-ray source, and supernovae remnants are the brightest X-ray sources in our galaxy and the galaxies similar to ours e.g., M31. About 200 X-ray binaries in which release of gravitational energy by the accreting matter is the main mechanism for X-ray generation, have so far been detected in our galaxy and a few in neighboring galaxies like Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC)[4]. In a majority of these binaries a spinning neutron star is the X-ray source while in about 20 objects there is evidence for the presence of a black hole. There is another class of binary sources with much lower X-ray luminosity ($\sim 10^{33}$ to 10^{34}ergs per sec) in which the accreting source is a white dwarf. These are almost all cataclysmic variable stars with binary periods mostly in the range of a few hours. In a class of asynchronous white dwarf binaries in which the white dwarf has a magnetic field of about a few times 10^{6} Gauss, the accretion flow is channeled to the magnetic poles resulting in X-ray pulsations with periods in the range of ~ 1000 to 2000 s. Abour 170 SNRs have been detected in our galaxy mainly from their non-thermal radio emission. Almost all are X-ray sources with luminosity in the range of $\sim 10^{35}$ to 10^{36} ergs per sec. A large number of SNRs have also been detected in LMC and SMC. Detailed studies of SNRs such as their surface brightness distribution, size, luminosity and spectral characteristics provide a wealth of information about the SNRs and their surrounding medium.

In this paper we will limit our discussion to the X-ray binaries with a neutron star or a black hole source.

X-ray Binaries : Present State of Our Knowledge

The first X-ray binary to be discovered was Cen X-3 in which regular X-ray pulsations with a period of 4.8 s and periodic X-ray eclipses occurring every 2.1 day were found with the UHURU satellite[5,6]. The X-ray eclipses were attributed to the occultation of the compact X-ray star by its large size optical companion star in a binary. The binary interpretation was also supported by the periodic Doppler shift observed in the X-ray pulsation period. The optical companion of the X-ray source in Cen X-3 was soon identified with a 13th magnitude O spectral type star whose brightness varies with the 2.1 day binary period.7 The discovery of Cen X-3 was soon followed by that of another binary Her X-1 which was found to have a pulsation period of 1.24 s, X-ray eclipses every 1.7 day and an on-off cycle of 35 days[8]. Since then a large number of X-ray binaries have been detected with several satellites. General properties of X-ray binaries have been summarized in a recent review by White *et al.*[9]

The X-ray binaries can be classified broadly in two categories known as low Mass X-ray Binaries (LMXBs) and High Mass X-ray Binaries (HMXBs). This classification is primarily based on the spectral type of the optical companion which in turn governs the accretion process. About two third of the known binaries are LMXBs. The catalog of X-ray binaries compiled by van Paradijs lists 124 LMXBs and 69 HMXBs.[4] Almost all the bright galactic bulge sources are LMXBs. We briefly describe the main characteristics of the two types of binaries in the following sections.

a) Low Mass X-ray Binaries (LMXBs)

The optical star in the LMXBs is usually a low mass object of spectral type F or later. The mass loss rate of these stars through the stellar wind is rather low and therefore the mass accretion occurs only when the star fills its Roche lobe. The mass lost from the overflowing Roche lobe is captured by the neutron star or the black hole. The captured material has angular momentum and therefore goes into orbit around the compact object and forms an accretion disc. The neutron stars in the LMXBs usually have a weaker magnetic field (less than 10^{11} Gauss) and therefore the disk comes very close to the neutron star surface or may even touch it. The X-rays come either from the inner hotter part of the accretion disk or from the boundary layer between the neutron star and the disk. Since the accretion flow is not channeled to the magnetic poles, the LMXBs usually do not have X-ray pulsations. The four exceptions to this are Her X-1 4U 1627-673, X2259 + 587 and GX1 + 4 which have pulsation periods of 1.24, 7.7, 7.0 and 121s respectively. The orbital periods of LMXBs are generally less than a day with a majority of them with well determined periods in the range of ~1 to ~10 hours. The well known binary 4U1820-303 located in the globular cluster NGC 6624, has the shortest period of 11 minutes among all the known binaries. X-ray eclipses and irregular dips are seen in the light curves of several LMXBs. The dips are interpreted as due to absorption of X-rays by the matter in the accretion stream passing in the line of sight. The X-ray luminosity of LMXBs lie in the range of 10^{35} to 10^{38} ergs per sec, the high luminosity ones being mostly in the galactic bulge region. The continuum X-ray spectra of the low luminosity LMXBs are generally complex and require two component fit. The spectra of high luminosity LMXBs are well described by a simple power law with a photon index of ~2 and an exponential high energy cutoff.

Besides the orbital modulation of the X-ray intensity, the LMXBs show irregular flickering and flaring activity, on a variety of time scales. An important characteristics that is found only in the LMXBs is the occurrence of 'X-ray Bursts' which usually occur irregularly but some times also regularly. Such bursts have so far been detected from about 40 LMXBs but none from any of the HMXBs.[10] Most X-ray bursts are of type 1 which are due to thermonuclear flashes on the surface of the neutron star. There is only one source known as 'Rapid Burster' which gives out type II bursts which are believed to have a different origin, most likely due to as yet poorly understood instabilities in the inner part of the accretion disc Presence of Quasi-Periodic Oscillations (QPOs) is another variability phenomenon exhibited by both types of X-ray binaries. Such QPOs have been detected so far from about 20 LMXBs and till recently the frequency of the QPOs were in the range of about 6 to 60 Hz range. Very high frequency QPOs termed as "kHz QPOs" which have frequency of upto about 1200 Hz have recently been reported from several LMXBs like Sco X-1, 4U 1608-52 and 9 other objects.[11-13] The low frequency QPOs can be explained well by the 'Beat Frequency' model of Alpar and Shaham in which QPOs are explained as arising due to 'clumps' of matter rotating near the inner accretion disc close to the neutron star magnetosphere.[14] The accretion of the clumps at nearly regular periods produces the X-ray oscillations and the oscillation frequency is the beat frequency between the Keplerian frequency of the disk and the rotation frequency of the neutron star. The origin of the kHz QPOs is yet to be explained statisfactorily.

b) High Mass X-ray Binaries (HMXBs)

The HMXBs generally have a massive O, B spectral type optical companion which loses mass *via* a strong stellar wind with mass loss at a rate of about 10^{-5} to 10^{-9} $M_\odot$ per year. A fraction of the mass lost from the optical star is captured by the compact star and the release of gravitational energy by the accreting matter leads to the production of X-rays. In some HMXBs the mass accretion occurs *via* Roche lobe overflow as is the case with Cyg X-1. The matter accreting *via* the stellar wind or the Roche lobe overflow gets ionized as it approaches the neutron star surface. The HMXBs have strong magnetic fields with a value in the range of ~10^{12} to 10^{13} Gauss. The ionized matter is guided by the dipole field to the magnetic polar caps of the neutron star and releases kinetic energy which heats up the caps to a temperature in excess of 10^7 K giving rise to X-ray emission. An accretion column is also formed above the polar caps. The X-rays from the polar caps and the hot gas in the accretion column produce a pencil or fan shape beam pattern. If the magnetic axis and the rotation axis of the neutron star are not aligned, then the spinning of the star on its axis will result in X-ray pulsations if the observer is located in the path of the beam. Three of the HMXBs namely Cyg X-1, LMC X-3 and LMC X-4 are also likely to be black holes. In these systems the accreting matter forms an accretion disk around the black hole. As the accreting matter in the disk rotates and gradually spirals in, the viscous friction causes heating of the disk and the inner regions of the disc near the black hole attain temperatures in excess of 10^8 K. This hot region of the disk produces low energy X-rays. Inverse Compton scattering of the optical and ultraviolet photons by the 'hot' thermal electrons in the inner accretions disk as well as in the corona surrounding the disk, gives rise to hard X-rays. The energy spectra of the HMXBs are harder than those of the LMXBs and are usually well fitted by a flat power law model with photon index of about 1 to 2. There is a cut-off energy above which the spectrum steepens rapidly with typical value of about 20 keV. Cyclotron lines have also been reported in the spectra of several X-ray pulsars mostly as absorption features. The energy of the cyclotron feature provides a direct measurement of the magnetic field of the neutron star. So far cyclotron lines have been reported in the spectra of 9 X-ray pulsars. These include Her X-1 with a line at ~35 keV and Cep X-4 at 32 keV.[15,16] The values of the neutron star magnetic fields derived from these lines lie in the range of $(1-4) \times 10^{12}$ Gauss.

The Studies of X-ray Binaries with Satellites : Present International Status

The X-ray binaries provide a wealth of astrophysical information about the nature of the X-ray producing compact stars, estimation of their masses, the magnetic field of the neutron stars in the pulsating binaries, the radiation environment of the source and details of the accretion process at work in them. The temporal and spectral observations with a number of X-ray satellites in the recent past have greatly advanced our knowledge about the high energy processes going on in these objects. The first candidate for a stellar mass black hole namely Cyg X-1 was discovered in X-rays. Recent discoveries of many transient X-ray sources and optical studies of the companion stars, have now provided more credible evidence for the existence of black holes in many X-ray binaries. The most notable black hole binaries discovered recently are GS 1124-68 (Nova Mus 1991), GRO J1655-40 (Nova Sco 1994) and GRO J0422 + 32 (Nova Per 1992) for all of which the mass of the X-ray source is measured to be in the range of 3.6 to 5.4 $M_\odot$ and therefore most likely to be black holes.[17] The field of accretion physics developed rapidly after the discovery of accreting X-ray binaries. The most rapid brightness variations among all the wavelength bands down to a time scale of 0.1ms, have been observed in X-ray binaries. The X-ray binaries have therefore been at the forefront of research in X-ray astronomy.

The binary studies broadly fall in two categories, the 'X-ray photometric' studies and the X-ray spectroscopic' studies. We discuss below some new developments in these areas.

a) X-Ray Photometry

The photometric studies are primarily aimed at the measurement of periodic and aperiodic intensity variations of sources over a wide time domain. These lead to the detection of regular pulsations, binary nature from eclipses and intensity modulation in the light curve, quasi-periodic oscillations, flares and other sporadic variations. Generally non-imaging collimated photon collecting detectors like proportional counters and inorganic scintillation counters, which have relatively poor energy resolution, have been used in the satellite missions for the temporal studies. They have the advantage of wide spectral band and realization of large collecting area at modest costs. The photon collecting detectors are therefore preferred for photometry of bright (~ 0.5 mCrab) sources while due to their greater sensitivity, the imaging instruments have to be used for studying fainter binaries.

There are three operating satellites dedicated exclusively to X-ray astronomy research at present. These are: ROSAT, a German satellite with X-ray imaging telescope sensitive in 0.1-2 keV meant for imaging observations, the Japanese ASCA satellite aimed at X-ray spectroscopy in 0.5-10 keV band and RXTE (Rossi X-ray Timing Explorer) which is a US satellite meant primarily for temporal investigations. The RXTE launched about 2 years ago carries Xenon-filled proportional counter array (PCA) with a collecting area of about 6000 cm^2 and sensitive in 2-60keV interval. It also has a cluster of phoswhich detectors with an area of 1600 cm^2 for hard X-ray studies in ~10ke V to several hundred keV range. The PCA has very fine time resolution with capability to register arrival time of photons to a precision of about one microsecond. This timing capability and the large collecting area has made it possible to study very rapid variability due to accretion flows close to the neutron star and black hole. An Indian X-ray Astronomy Experiment (IXAE) launched on the Indian satellite IRS-P3 on 1996, March 21, is also operational and is providing good quality timing data. Results from IXAE will be described in a separate section.

As mentioned earlier discovery of kHz QPOs is a major finding of the RXTE mission. From high time resolution observations, the kHz QPOs have been discovered so far in 11 LMXBs and in 8 of these two QPO peaks are present simultaneously. The lower frequency peak is in 300-900 Hz range while the higher one is in 500-1200 Hz range. The frequencies of both the peaks increase with increase in the source intensity but the difference between the two frequencies remains constant except in the case of Sco X-1. The amplitudes of the kHz QPOs are in the range of 3 to 15 percent of the total flux in 2-20 keV interval. The 'Quality' factor, which is defined as the ratio of the centroid frequency of the peak to its full width at half maximum, is found to be as high as 100 and more, being ~900 for KS 1731-260 during a burst.[18] A recent summary of the kHz QPOs can be found in the review of van der Klis.[11]

In the case of the LMXB KS 1731-260, two QPO peaks were detected with the RXTE on 1996, August 1 at frequencies of 898 and 1159 Hz with amplitude of about 5%. The observed QPOs are shown in Fig. 1 taken from Wijnands and van der Klis.[19] The frequency difference between the two peaks in 261Hz which is one half of the frequency of the QPOs observed from this object by Smith *et al.*[18] during occurrence of a burst. It has been suggested by Wijnands and van der Klis that the higher frequency QPO represent the preferred orbit of the matter orbiting the neutron star while the difference frequency of 261Hz corresponding to a period of 3.8ms, is the spin frequency of the neutron star. The lower frequency is then the beat frequency between the spin frequency of the neutron star and the higher frequency of the matter orbiting near the neutron star. If this interpretation is correct then this provides the first observational evidence that the LMXBs are indeed the progenitors of the Millisecond pulsars. Another LMXB 4U 0614 + 091 was observed three times with the PCA on RXTE in different intensity states. The QPOs were found to be present at all intensity levels but in the brighter state two QPO peaks were observed. The difference in the centroid frequencies of the two QPO peaks was found to be constant at a value of 232Hz (period of 3.3ms) even though the centroid frequencies of the QPO peaks varied systematically with the count rates. As in the case of KS 1731-260, this difference is interpreted as the spin period of the neutron star while the highest frequency is explained as the orbital period of the matter at the inner region of the accretion disk closest to the neutron star.[20] The neutron star spin period of 3.3ms is consistent with the hypothesis of LMXBs being the parent stars of the millisecond pulsars. From further spectral and temporal analysis of the PCA data for 4U 0614+091, Ford *et al.*[21] found that the spectrum of this object requires a two component fit, a power law with slope of ~2.8 and a blackbody with kT ~1.5 keV. The blackbody component constitutes about 10 to 20% of the total energy flux. It was found that the frequency of the higher frequency QPO shows a tight correlation with the blackbody flux as shown in Fig. 2 taken from Ford *et al.*[21] As the flux increases the QPO frequency also increases.

The highest observed frequency of the QPOs in the LMXBs is about 1200 Hz. Zhang *et al.*[22] have suggested that this is the frequency of the marginally stable orbit of matter orbiting closest to the neutron star. Since the neutron star has to be within this orbit, tight constraints can be placed on the size and mass of the neutron star. Using kHz QPO data for eight of the LMXBs, Zhang *et al.* find that the masses of the neutron star in these binaries are about 2 $M_\odot$. A similar mass limit for the neutron star has been arrived at independently by Smale *et al.*[23] from kHz QPOs

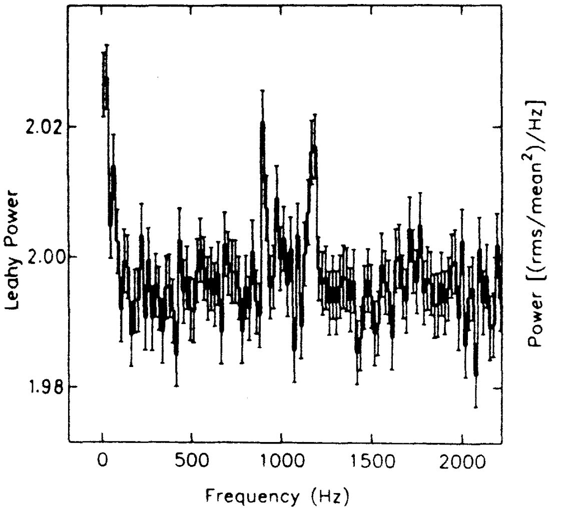


Fig 1 Normalized power spectrum of the low mass X-ray source K S 1731-260 obtained from the PCA observations made on 1996 August 31 in (5.7-24.1 keV) band. Two QPO peaks at frequencies of 900Hz and 1176Hz are visible in the figure. Fig taken from Wijnands and van der Klis (Ref. 19)

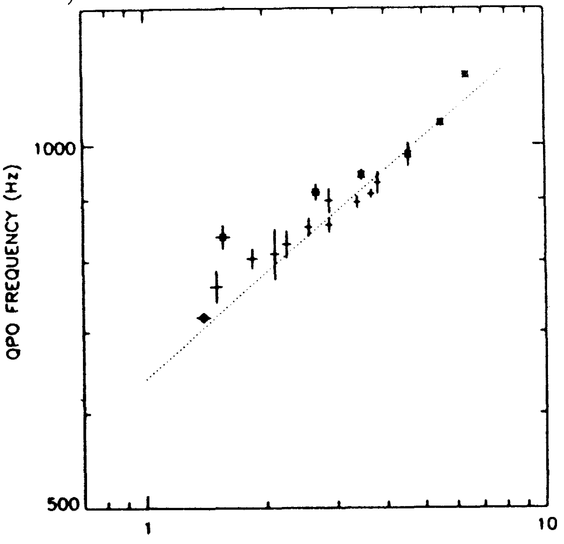


Fig 2 The correlation of the QPO frequency with the Blackbody spectral component is shown in this plot for the source 4U 0614+091 taken from Ford *et al.* (Ref. 21)

observed from the binary 4U 1820-30 and by Ford *et al.*[20] from the kHz QPOs in 4U 0614 + 091.

The timing studies with the RXTE and IXAE have also provided valuable information about the accretion process in the black hole binaries like Cyg-X-1 and GRS 1915 + 105. These studies are based on the timing analysis of intensity in different intensity states of Cyg X-1 with fine time resolution and then constructing the power density spectra (PDS) to derive source behaviour in different time domains. The GRS 1915+105 results are based on study of QPOs at different intensity levels and also timing and spectral analysis of the regular and irregular bursts and dips observed in this unique object which will be discussed in detail in a later section.

From analysis of X-ray pulsations in GX 1 + 4 and GRO J1744-28 at different intensity levels, Cui[24] has provided observational evidence for the existence of 'propeller' effect which though predicted long ago, was not detected so far. In accretion powered pulsating X-ray binaries, a neutron star with a magnetic field of $\sim 10^{12}$ to 10^{13} Gauss, accretes matter from its normal companion star. The neutron star has a magnetosphere which co-rotates with it. The ram pressure of the accreting matter is balanced by the magnetic pressure and if the mass accretion rate is high, as is the case in the X-ray bright state, then the magnetosphere is compressed and is within the corotation radius. In such a situation the accretion flow is channeled to the magnetic poles and the hot spots at the two poles produce X-rays. Rotation of the neutron star causes X-ray pulsations if the magnetic and rotation axes are not aligned. When the X-ray source is in a low intensity state, the accretion rate is low so that the magnetosphere grows larger than the co-rotation radius due to lower ram pressure. As a result the accreting matter is not able to penetrate the magnetosphere and is 'propelled[2] away by the centrifugal force. Cui[24] found that in GX 1+4 and GRO J 1744-28, strong pulsations were present and the pulse fraction was large when the X-ray flux from the sources was high. When the two sources were observed in the faint state, the pulsations were either barely detectable or not detected at all due to very low pulse fraction consistent with the prediction of the binary models.

b) X-ray Spectroscopy

The launch of the Japanese Satellite ASCA in February 1993 marked the beginning of a new era in *x*-ray astronomy as this X-ray observatory, principally aimed at the spectroscopic studies of X-ray sources, made it possible to study emission and absorption features in the X-ray spectra with non-dispersive detectors with a resolution better than that of any previous mission. The ASCA satellite carries an X-ray imaging mirror made of nested conical foils with a Solid state Imaging Spectrometer (SIS) and a Gas Scintillation Imaging Spectrometer (GIG) at the focal plane of the mirror assembly. The SIS based on the use of CCD detector has a typical energy resolution of about 100 eV at 6 keV and thus a factor of about 2 better than that of the Solid State Detector used on the Einstein Observatory.

The detection of X-ray lines and measurements of their strengths and profiles is a powerful tool to determine elemental abundance, temperature, density and radiation field in and nearby regions of the binary sources. Several binary sources have been observed with ASCA and their spectra reveal a variety of lines due to H-like and He-like ions of different abundant elements. The energy spectrum of the low mass binary 4U 1626-67 shows a strong neon line complex at about 1 keV besides weaker lines of Mg and O. The most prominent feature is the Ne Lyman Alpha line at 1.08 keV. The best fit spectrum requires overabundance of neon relative to the solar value by a factor of 6 and this can be explained if the companion star is burning helium as neon is a by-product of this process.[25] The X-ray spectrum of Her X-1 shows strong 6.4 keV iron fluorescent line besides neon lines due to H and He-like ions. The SIS spectra of several other pulsars like GX 301-2, GX 1+4 etc. show strong fluorescent lines of Fe, Mg, Si and S which originate in cold, low ionization medium showing that photoionization is rather low in these systems. The spectra of Cen X-3 and Vela X-1 on the other hand, show prominent recombination K-Alpha lines of H and He-like ions of Mg. Si, S, Ar and Fe. This suggests that the lines are produced in a highly photoionized plasma surrounding the sources which has an abundance of H and He-lime ions due to intense X-ray irradiation from the neutron star. Nagase *et al.*[26] have carried out phase resolved spectroscopy of the X-ray binary pulsar Vela X-1 with SIS during the post-eclipse, pre-eclipse and eclipse phases. Besides the 6.4 keV Fe fluorescent line, the other prominent lines are identified as K-Alpha lines of He-like ions of Ne, Mg and Si. Even the eclipse phase spectrum is dominated by lines of He-like ions which suggests that the lines are produced by radiative recombination process in the photoionized stellar wind of the companion star. Spectra of several other binaries notably Cyg X-3 show similar spectra with presence of prominent radiative recombination lines as shown in the SIS spectrum of Cyg X-3 in Fig. 3 obtained by Liedahl and Paerels.[27] This again suggests that the source has photoionized circumstellar envelope in which the lines are produced.

Indian Contributions to the Studies of X-ray Binaries

The X-ray astronomy research was initiated in India in 1968 when the first hard X-ray observations of the binary Sco X-1 were carried out in 20-100 keV band with a balloon-borne instrument. Around the same time low energy X-ray observations were carried out in rocket flights by a group at PRL in collaboration with a Japanese group.

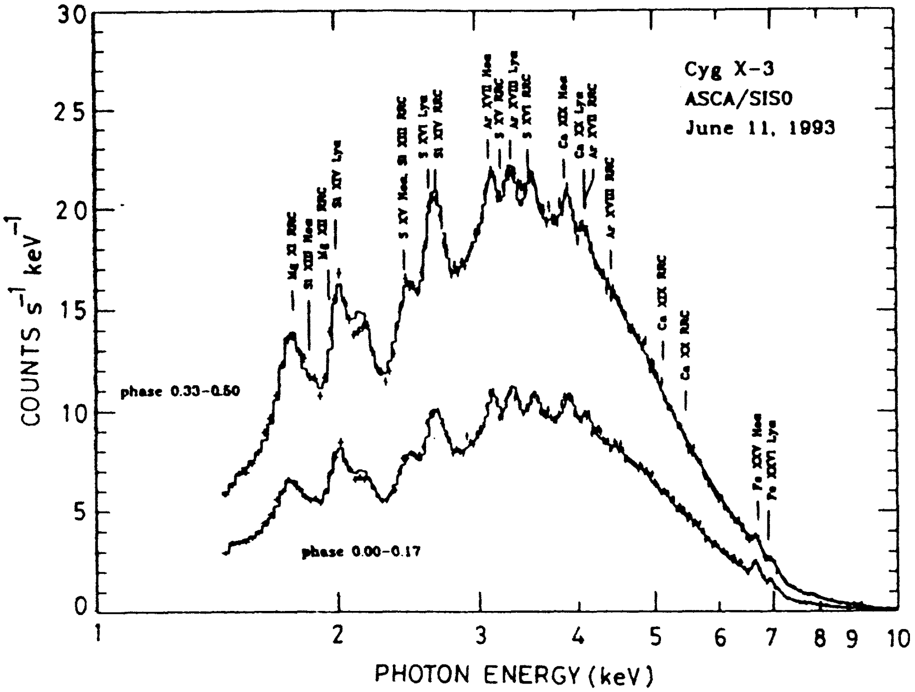


Fig 3 Energy spectra of the 4.8 hour binary Cyg X-3 at two different phases obtained with the CCD spectrometer on the ASCA satellite. Several X-ray emission lines due to H-like and He-like ions of various elements are seen in the spectra. Taken from Liedahl and Paerels (Ref. 27)

These were followed by a series of observations of several bright X-ray binaries with balloon-borne instruments by groups at TIFR and PRL. The instruments used collimated sodium iodide detectors of about $100cm^2$ area mounted on an orientable platform. Some of the noteworthy results from these studies were : (1) Measurement of the hard X-ray spectra of Sco X-1, Cyg X-1, Her X-1, Aql X-1 and the cosmic diffuse X-ray background. (11) Detection of rapid flux variations in Sco X-1 and Cyg X-1 (III) Detection of the first hard X-ray flare in Cyg X-1[28] (IV) Measurement of the correlated optical and hard X-ray variations in Sco X-1 in collaboration with the Japanese groups[29]. A collimated proportional counter flown on the first Indian satellite Aryabhatta provided limited observations of Cyg X-1 and a few other binaries for a few days before the failure of the satellite power system.

The hard X-ray studies of the X-ray binaries are being carried out by the TIFR group with a large area Xenon-filled multilayer proportional Counter (XMPC) telescope which is flown from Hyderabad by large volume plastic balloons to an altitude of about 40km. The low energy (2-20 keV) studies are currently being carried out with the Indian X-ray Astronomy Experiment (IXAE) on the Indian satellite IRS-P3 launched on 1996, March 21. The details of the instruments and some of the important results from these experiments are described in the following sections.

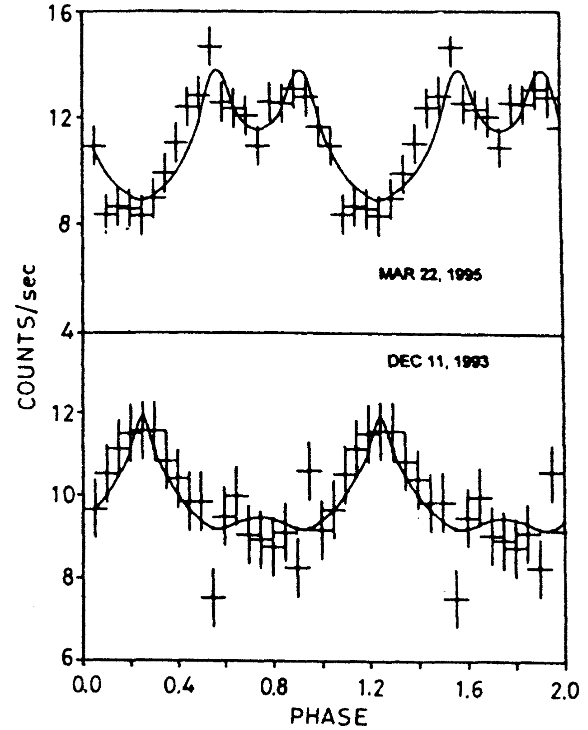


Fig 4 Pulse profiles of the *x*-ray pulsar GX 1+4 in 20-100 keV band obtained from two balloon-borne observations, one in Dec., 1993 and the second in March, 1995. Change in the pulse shape from single peak pulse to a double-peak one is clearly visible. Taken from Paul *et al.* (Ref. 34).

a) Current Status of Hard X-ray Studies of X-ray Binaries in India

The TIFR group successfully developed a new oriented hard X-ray telescope in mid eighties to study spectral and temporal characteristics of binary X-ray sources. The telescope consists of a pair of xenon-filled multilayer proportional counters (XMPC) with an effective area of about 2500cm^2 and mounted on a platform which can be oriented in azimuth as well as elevation to an accuracy of about 0.3 degree. The XMPC have a field of view of about 5° × 5° defined by honeycomb collimators made of a tin and copper. The XMPC, sensitive in the 20-100keV band, have an average detection efficiency of about 50% in the 20-100keV interval and an energy resolution of about 10% at 22keV. The telescope can be programmed to track any given source automatically by an onboard tracker. This instrument has been flown successfully in about a dozen balloon flights and several X-ray pulsars and binaries have been studied in these experiments. These include Cyg X-1, Cyg X-3, 4U 1907+09 and GX 1+4. Details of the XMPC have been given by Agrawal *et al*[30].

The 4.8 hour period binary Cyg X-3 was observed with the XMPC telescope in 1991. Modulation of the hard X-ray flux with the 4.8 hour period was clearly detected and the energy spectrum of the source was obtained. There was also indication of quasi-periodic oscillations with a period of about 120s during a part of the observations.31 The 8.9 day period binary 4U 1907+09 which has an X-ray pulsar with a period of 430s, was observed two times and found to be in a faint state. As a result X-ray pulsations were not detected but the energy spectrum was measured for the first time in the hard X-ray region and found to be a power law with photon index of –1.4.[32]

The most important results on binary sources from the XMPC observations concern the X-ray pulsar GX 1+4 which has pulsation period of about 122s. Since its discovery in 1970 in a balloon flight, it was spinning up till 1983 when it made a transition to a low state and became undetectable. It had the highest spin-up rate, ($\dot{p}/p$) of about -2s per year, among all the X-ray pulsars. When detected again in 1987 it was found to be spinning down with a period of 122s. This pulsar was observed in a balloon flight on 11 December, 1993 with the XMPC telescope. The X-ray pulsations were clearly detected with a period of 121.0s consistent with the spin-down trend. The pulse fraction was found to be about 30% and there was an indication of anticorrelation between the pulse fraction and the source luminosity. The X-ray spectrum with a power law slope of -1.6 was found to be the hardest among all the measurements so far.[33] Observations of GX 1+4 were again made in another balloon flight on 22nd March, 1995. The pulsar was detected and from the measured period a spin-down rate of 0.72s per year was obtained. The most interesting result was that the shape of the X-ray pulse was found to have changed from a single peak shaped pulse to a double-peaked shape profile as shown in Fig. 4 taken from Paul *et al.*[34] This change in the pulse shape can be explained either due to activation of both the poles of the neutron star or by change from a pencil beam to a fan beam. Further studies of this fascinating pulsar in different intensity states will be valuable in understanding its behavior.

The bright X-ray binary Cyg X-1 which is a strong candidate for a black hole and is the brightest X-ray source above 20keV, was observed several times with the XMPC telescope. Due to their better energy resolution, typically about 10% FWHM at 22 keV, the XMPC detectors are well suited for accurate spectral measurements of the X-ray continuum. In a balloon observation made on April 5/6, 1992 Cyg X-1 was detected at a count rate of ~25 counts per s in each detector. Using the detector response matrix obtained from the laboratory calibration data, the observed pulse height spectra were used to derive the source spectrum. It was found that a simple power law with a photon index of –1.62 or a thermal-Compton model with electron temperature kT=25 keV gave equally acceptable fits. In order to distinguish between the models, the energy spectrum was constructed over a wider band from 2-500 keV by combining data from EXOSAT Medium Energy (ME) and the GSPC detectors, the XMPC telescope and the Oriented Scintillation Spectrometer Experiment (OSSE) data in 50-500 keV band. By making a combined fit to the data from all these instruments covering energy interval from 2-500 ke V, it is found that a two component Comptonisation model represents the continuum x-ray spectrum of Cyg X-1 rather well. The observed count rate spectra along with the best fit model are shown in Fig. 5 taken from Chitnis *et al.*[35]

Development of a new hard X-ray telescope with better sensitivity and improved energy resolution is in progress at TIFR to study fainter binary sources and measure spectra of Active Galactic Nuclei above 20 keV. A hard X-ray instrument which employs sodium iodide detectors in a back to back configuration, has also been developed and has been tested successfully in balloon flights.[36]

b) Binary Studies in 2-20 keV Band with the Indian X-ray Astronomy Experiment (IXAE)

An X-ray astronomy experiment consisting of 3 coaligned collimated proportional counters and an X-ray sky monitor was launched from India onboard the Indian satellite IRS-P3 on March 21, 1996 with a PSLV rocket. The principal objective of this experiment is to investigate short and long term variability of X-ray binaries and other variable sources. A star tracker with its view axis parallel to the axes of the 3 proportional counters, is used to acquire and point at the target source for making pointed-mode observations. The X-ray instrument has been performing satisfactorily since the launch and has been used to observe variability of several binary sources including the black hole binaries Cyg X-1 and GRS 1915 + 105, 4U 1907 + 09 and GX 1 + 4. Some of the important results from this experiment are discussed below.

Details of the Indian X-ray Astronomy Experiment: A set of 3 identical collimated proportional counters with an effective area of about 1200cm^2 and equipped with collimators with a field of view (FOV) of 2°.3 × 2°.3 constitute the principal instrument of the Indian X-ray Astronomy Experiment (IXAE). These counters are used to make pointed-mode observations and hence have been named as Pointed-mode Proportional Counters (PPCs). Each PPC is a multilayer detector with 54 anode cells arranged in 3 identical layers. Each anode cell has size of 11mm × 11mm and consists of a 25 micron diameter gold plated stainless steel wire surrounded by ground planes of beryllium-copper wires. Eighteen cells of the third layer and the end cells of the top two layers are connected together to form a veto layer which is operated in anti coincidence with the first two X-ray detection layers to reject the charged particle background. The alternate cells of the top two layers are also linked together and operated in mutual anti coincidence to reject non-cosmic X-ray background produced by Compton scattering of high energy photons. The PPCs are filled with a 90% argon + 10% methane gas mixture at 800torr with a 25 micron thick aluminized mylar film serving as the gas barrier. The collimators are made from 0.15 mm thick aluminum slats coated with 6 micron thick silver and corrugated with rectangular shaped wells. X-rays of 22.2keV from a highly collimated Cadmium-109 radioactive source mounted at the rear of each PPC, are used to continuously monitor gas gain of the PPCs. From each PPC five count rates are recorded: 2-6keV and 2-18keV counts from the first layer, 2-18 ke V counts from the second layer, veto layer counts and all the counts which exceed the upper level of the comparator set at 30keV. In the normal mode the integration time for all the counts is 1s which can be changed by command to 10ms, 100ms and 10s. There is also a 'pulsar' mode for data acquisition in which each photon can be time tagged to an accuracy of 0.4ms using an anboard oven-controlled crystal clock. Pulse height analysis of all the valid events is carried out with a 64 channel analyzer and onboard histograms are generated with integration time of 100s in normal mode and changeable by command to 1s, 10s and 1000s. The average detection efficiency of PPCs is about 50% in 2-10keV band and drops to about 10% at 20keV. Typical energy resolution averaged over the entire detector is about 22% at 6keV. For a more complete description of the IXAE refer to Agrawal *et al.*[37] and Agrawal.[38]

The IRS-P3 satellite is in a circular, polar Sun-synchronous orbit with an altitude of 830km and orbital inclination of 98° with the equatorial plane. The polar orbit of the satellite severely restricts the time for which useful data can be obtained. This is due to the fact that the satellite spends a lot of time at the high latitude regions (>|60| degrees) and most of the orbits also pass through the South Atlantic Anomaly zone. The charged particle background is very high in the polar and SAA regions producing a high and variable background. This greatly restricts the useful observing time which is typically about 20min. per orbit in 7 of the 14 orbits per day.

The PPCs were calibrated by pointing at the well known bright X-ray source Crab Nebula which has a constant intensity and an angular size of about 1 arc minute. The 33ms pulsar NP 0531 + 21, which is a bright pulsating source, is located in the crab Nebula. The FOV of the PPCs were calibrated by scanning across the Crab Nebula in the pitch and yaw directions and found to be 2°.3 × 2°.3. The detector response functions have also been obtained from the calibration. Strong X-ray pulsations with 33ms period were clearly detected in the 3 PPCs. A typical X-ray pulse profile observed with PPC 1 from the Crab pulsar is shown is Fig. 6.

Black Hole Binary Cygnus X-1: This is a bright X-ray binary with a period of 5.6 day in which the X-ray source is inferred to be a black hole based on the estimate of its mass which greatly exceeds the permitted mass limit for a neutron star. The source has two distinct intensity or spectral states and makes transition from one state to the other at irregular intervals. Most of the time Cyg-X-1 is found in the 'low' (or hard) state and occasionally goes to the 'high' (or soft) state. In the performance verification phase of the IXAE, Cyg X-1 was observed during May 1-11, 1996 when it was in a low state. It was clearly detected in each PPC with a flux level of about 300-500m Crab. It was again observed during July 5-8, 1996 when it was in a bright state. An average flux of 800-1100mCrab was recorded in each PPC in the bright state. Most of the observations were made with a time resolution of 1s but some data were also taken with 0.1s and 0.4 ms resolution. The background was measured by pointing at a source-free region near Cyg X-1. The background subtracted light curves show rapid and chaotic variations in both the states, the variations being more pronounced in the low state. Typical light curves for the soft and hard states with a time resolution of 0.1s are shown in Fig. 7. Random intensity variations and flaring activity on time scale of 0.1s and longer can be seen clearly from the figure. Brusts of 0.1s and longer duration are visible in both the light curves, but the stronger bursts seem to be more frequent in the hard state.

Power density spectra (PDS) for the two states were obtained form the individual data segments and then added to construct the PDS shown for the two states in Fig 8. The hard state PDS is based on data with time resolution of 1s and 0.4ms while the data with resolution of 1s and 0.1s were used for the soft state PDS. The hard state PDS in 0.3

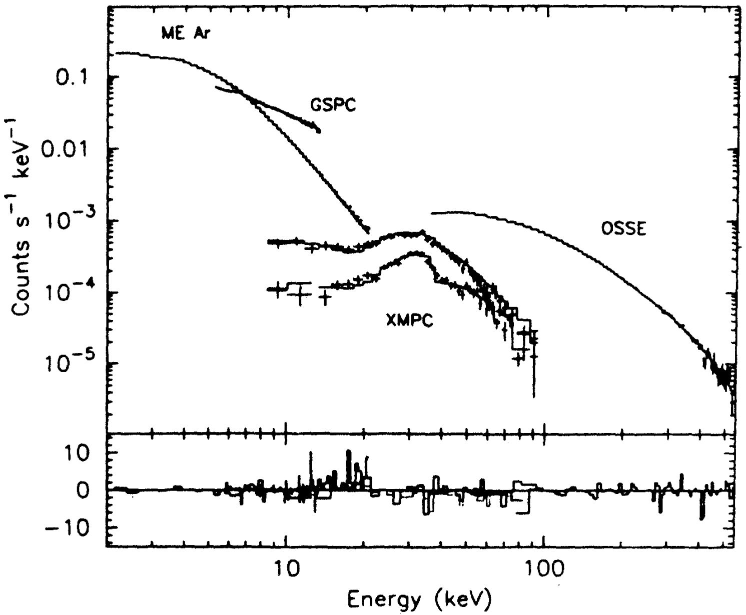


Fig 5 The energy spectrum of Cyg X-1 in 2-500 keV range obtained by combining data from EXOSAT ME detector, EXOSAT GSPC, Balloon-borne XMPC and the OSSE. The best fit multicomponent model is shown as histogram along with the observed count rate spectra. The residuals to the best fit model are shown in the bottom panel. Figure from Chitnis *et al.* (Ref. 35).

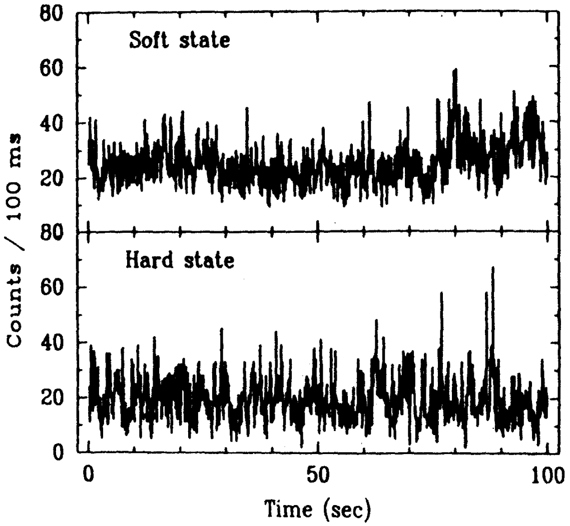
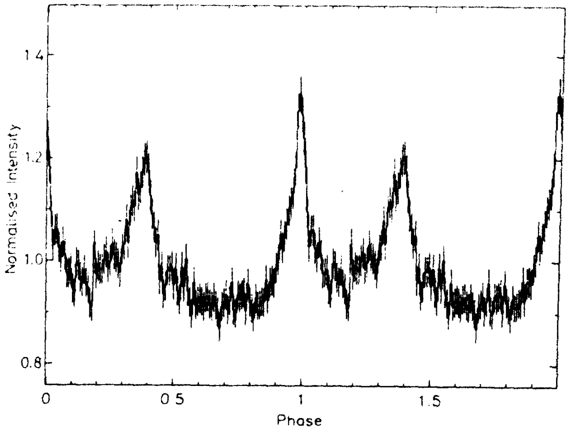


Fig 7 The X-ray light curves of Cyg X-1 obtained with the PPCs during the 'Soft' and 'Hard' states in May-June, 1996 with a time resolution of 0.1s. Flaring and flickering on time scale of 0.1s are seen in both the states.

Fig 6 The X-ray pulse profile observed with PPC1 from the 33 ms pulsar NP 0351+21 in the Crab Nebula during the calibration of the PPCs is shown. The main pulse and the interpulse are seen prominently in the figure.



to 10Hz band is well fitted by a power law with index of -1.1 but between .01 and 3.0Hz the PDS is flat with a break in slope at 0.3Hz. The general shape of the PDS obtained with the IXAE in the hard state in in agreement with the one measured by PCA on the RXTE in the transition state but the slope of the PDS obtained by us in .01 to 0.3Hz is flatter than that measured by the PCA. The soft state PDS can also be fitted with a power law with slope of -0.39 above .03 Hz indicating that it is flatter compared to the PDS in the hard state. A flattening below .03Hz can also be seen but there is no break in the slope. The present observations confirm that the PDS characteristics are dependent on the intensity state of the source and change smoothly as the source makes transition from one state to the other as also noted by Cui *et al.*[39] Analysis of Cyg X-1 variability has been carried out by applying 'shot' noise model of Terrell.[40] Background subtracted data with 1 s binning were used to compute shot frequency and duration. It is found that the shot distributions are well described by an exponential function of the form $f(s) = N \exp (S/C)$, where S is the number of photons in the shot. The e-folding constants of the fitted functions are 0.35 s for the hard state and 0.2 s for the soft state indicating that the longer shots are less frequent in the soft state compared to the hard one. A more complete discussion of the IXAE results on Cyg X-1 can be found in Rao *et al.*[41]

The Superluminal Source GRS 1915 + 105 : The transient source GRS 1915 + 105 discovered in 1992 with the WATCH experiment on the GRANAT satellite, is a strongly variable and flaring source in hard X-rays.[42] It has been identified with a variable radio source which shows flaring activity on a variety of time scales.[43] Based on the superluminal motion of its two symmetrically located jets, it has been termed as a micro quasar. Correlated hard X-ray and radio flux variations have also been observed from a long term monitoring of the source. It was first observed with the PPCs during July 23-27, 1996 and good quality data were obtained for a total exposure of 8850s. Almost all the data were acquired with a time resolution of 0.1s. The source was in a low (hard) state during these observations. The X-ray light curves generated after subtracting the background showed no significant variability on time scale of a minute or longer. Marked and chaotic intensity variations were, however, detected on time scale of 1s and less in all the observations. A few segments of light curves with a time resolution of 0.1s are shown in Fig. 9 taken from Paul *et al.*[44] Sub-second flaring activity is clearly seen in all the plots. Duration of the bursts range from 100ms to 400ms. This was the first reported observation of rapid variability of this source in 2-20keV band and showed that its variability behavior is remarkably similar to that of the black hole candidate Cyg X-1. A power density spectrum analysis showed presence of strong quasi-periodic oscillations (QPOs) at a frequency of about 0.7Hz. The QPOs are present in all the data and seen independently in all the 3 PPCs. A periodogram shown in Fig. 10 shows a strong QPO peak at 0.7Hz. A small hump seen at 1.4Hz is due to the first harmonic of the 0.7Hz QPOs. The QPO frequency varies from day to day in an erratic manner and was found in the range of 0.62 to 0.82Hz. The QPOs observed at the highest and lowest frequencies of 0.62Hz and 0.82Hz are shown in the inset of Fig. 12. The fractional rms amplitude of the QPOs is about 10%. The sub-second variability, presence of QPOs and power density spectrum similar to that of Cyg X-1, super-Eddington X-ray luminosity and peculiar radio characteristics all argue in favor of the X-ray source being a black hole. A more detailed description of the results from the 1996 observations of GRS 1915 + 105 has been given by Paul *et al.*[45]

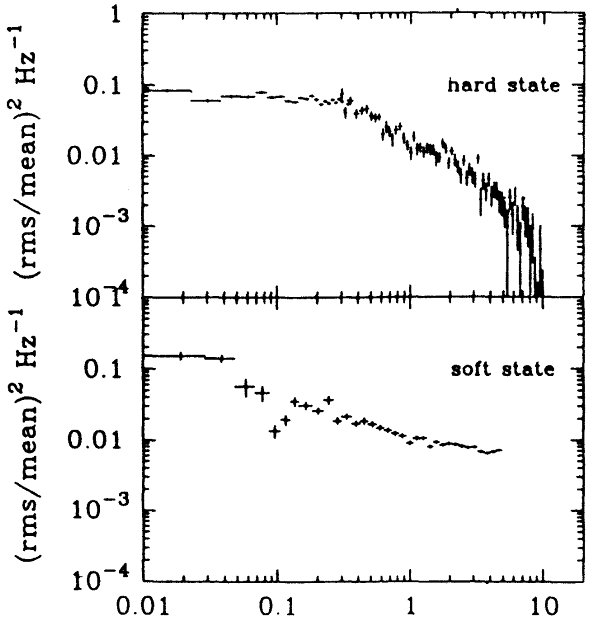


Fig 8 The power density spectra of Cyg X-1 in the 'Soft' and 'Hard' states obtained from the PPC data. The two PDS show a marked difference indicating the dependence of the PDS on the intensity state of the source. Taken from Rao *et al.* (Ref. 41)

An even more direct and convincing evidence for the black hole nature of GRS 1915 + 105 has come from the discovery of quasi-regular X-ray bursts with slow rise and fast decay times detected with the PPCs during the second observation of this source in the period June 12 to June 29, 1997. Strong bursts were detected during the entire observation period. The bursts are of three types : (I) regular bursts with a recurrence period of about 45s, width of about 10s and with slow rise and fast decay; (II) irregular bursts of variable duration having a flat top and with slow rise and fast decay; and (III) long duration bursts with duration ranging from a few tens of sec to a few hundred sec having a sharp decay. The regular bursts were detected during June 12-17 and again during June 22-26, the irregular bursts during June 18 to June 21 and the long duration bursts after June 27. Total useful source exposure time was 39,300s, during which 635 regular bursts, 78 irregular bursts and 40 long duration bursts were detected. The duration of the long bursts was found to be correlated to the quiescent state duration preceding the bursts. A plot of some representative bursts of 3 types detected on different days is shown in Fig. 11 taken from Paul *et al.*[46]

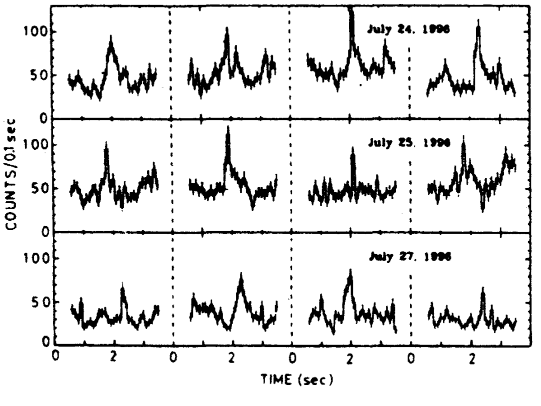


Fig 9 Rapid intensity variations on subsecond time scale in the superluminal source GRS 1915 + 105 observed with the PPCs on the IXAE are shown in these figures. Flux variations on time scale of 0.1 to 0.4s by a factor of 2 or more are clearly visible. (Taken from Paul *et al.*).[44]

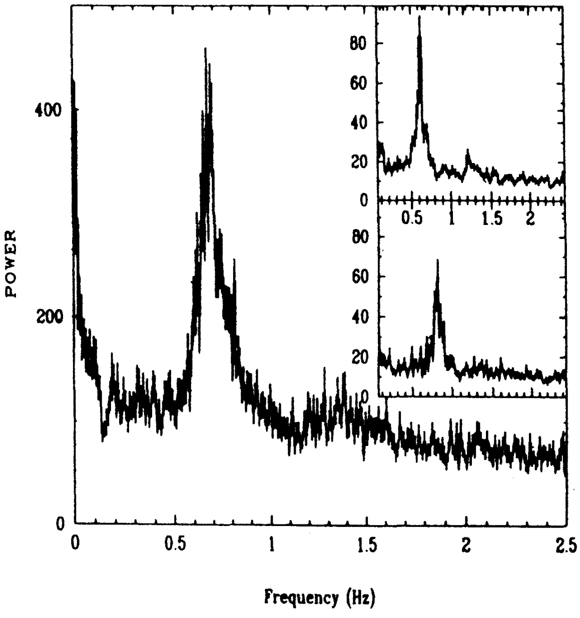


Fig 10 The power spectrum of GRS 1915 + 105 obtained from the PPC data shows a prominent peak at a frequency of about 0.7Hz due to presence of strong Quasi-Periodic Oscillations (QPOs). The highest and the lowest frequency QPOs at frequencies of 0.62 and 0.82Hz are shown in the inset (Taken from Paul *et al.*).[44]

The intensity of the regular bursts was about 3 to 5 times the quiescent value. In all the bursts a dip was found to be present just before the burst decayed. Another remarkable feature of the regular bursts was their persistence for several days with the same period and shape. Time interval between the regular bursts averaged over one day has a fair scatter and lies in the range of 40 to 52s. A typical burst with a fitted profile, which is a sum of two bursts with an exponential rise and fast linear decay, is shown in Fig. 12. The rise time of the bursts is about 7 to 10s and a linear decay time of 2 to 3s. By matching the peaks of the fitted burst profiles, a large number of bursts were added and the added burst profiles are shown in the 2-6keV and 6-18 keV bands in top two panels in Fig. 13 while the added profile for the total energy band of 2-18keV is shown in the third panel of the same figure. The hardness ratio defined as the ratio of 6-18keV counts divided by the 2-6 keV counts, is shown in the bottom panel of Fig. 13. It is immediately obvious from the figure that as the burst progresses, the hardness ratio increases and becomes maximum just before the end of its decay. They is in sharp contrast to the type 1 and type II bursts in LMXBs in which the spectrum is hardest at the peak and becomes softer during decay due to the radiative cooling of the plasma. The bursts in the LMXBs have a fast rise of ~1-10s and slow decay in an interval of 10sec to a few minutes. The type 1 bursts are produced by thermonuclear flashes on the surface of the neutron star while type II bursts are believed to be due to sudden infall of material on to the neutron star due to instability in the inner accretion disc. The regular bursts detected in GRS 1915 + 105 are distinct from the normal LMXB bursts in all these respects and therefore have a different origin.

Paul *et al.*[46] have attempted to explain the regular bursts in GRS 1915 + 105 in terms of advection effects in an accretion disk around a black hole. The ratio of the burst luminosity to the quiescence state luminosity is typically ~10 in the type 1 bursts and 0.4 – 2.2 in type II bursts. This ratio is about 0.3 – 0.5 for the regular bursts detected from GRS 1915 + 105. This suggests that the energy release mechanism is unlikely to be the thermonuclear process but more likely to be the gravitational energy release by the accretion of matter as this has much higher efficiency. However, all the released energy is not radiated and a significant part is advected into the event horizon of the black hole as the matter carrying the kinetic energy disappears behind the event horizon.[47] The regular bursts observed from GRS 1915 + 105 can be explained as periodic infall of matter into the black hole caused by an oscillating shock front acting on the sub-Keplerian component of the disk.[48] The mass of the black hole in GRS 1915 + 105 has been estimated to be 33 M.[49] Using this the oscillation period is computed to be about 50s, and the free fall time of matter is estimated to be about 8s consistent with the observations. The slow rise time of the bursts and the fast

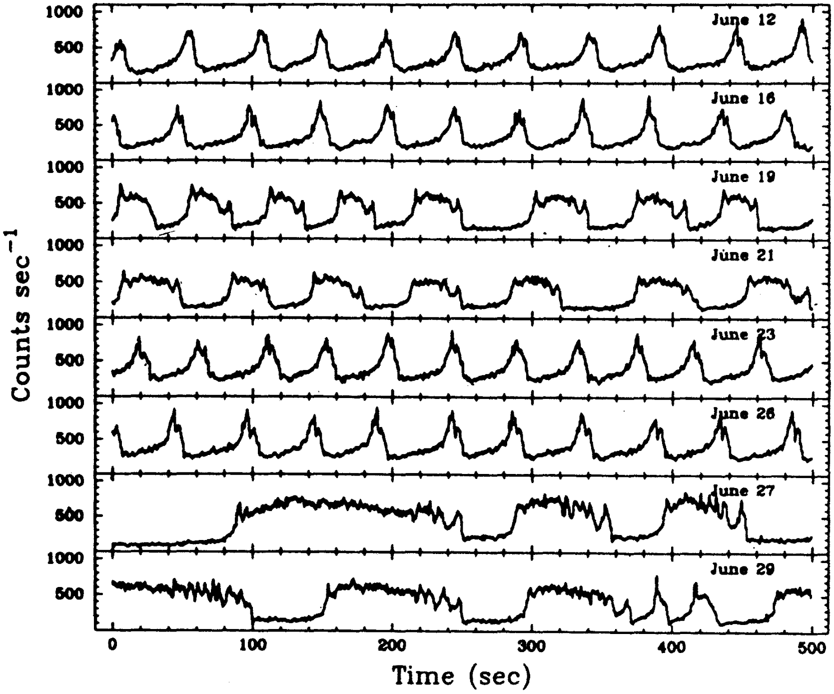
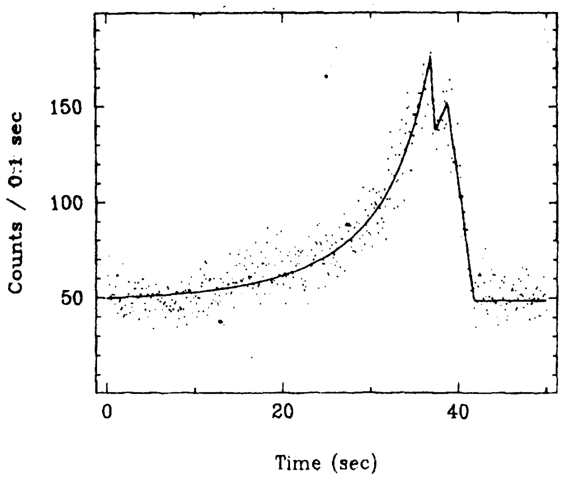


Fig 11 Regular and Irregular 'Bursts' detected from the black hole candidate source GRS 1915 + 105 with the PPCs on the Indian X-ray Astronomy Experiment aboard the Indian satellite IRS-P3. The observation were made in June 1997. (Taken from Paul *et al.*).[46]



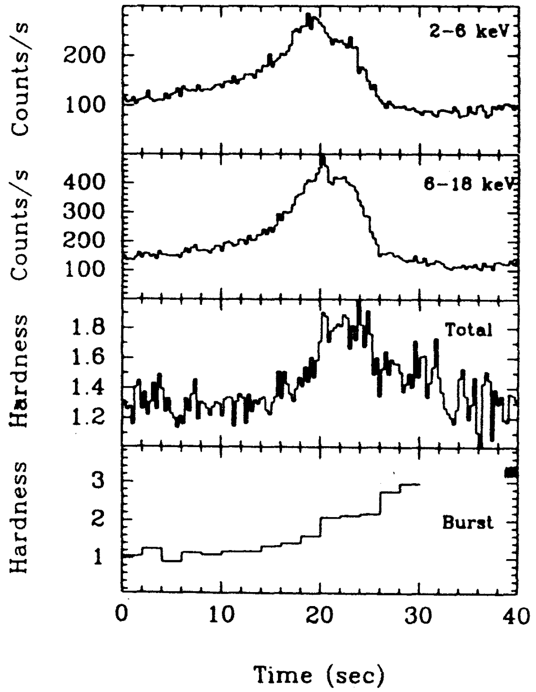


Fig 12 A typical profile of the 'Regular Bursts' with a recurrence time scale of 45s detected from GRS 1915+105 is shown. Note that unlike any other type of bursts detected earlier, these bursts have a slow rise with time scale of 7 to 10s and a fast linear decay in 2 to 3s. This is a unique feature of these bursts. (Taken from Paul *et al.*).[46]

Fig 13 The average profile of the regular bursts from GRS 1915 + 105 obtained by adding large number of bursts, is shown in different energy bands. The hardness ratio defined as the ratio of 6-18-keV counts divided by the 2-6-keV counts is shown in the bottom panel of the figure. (Taken from Paul *et al.*). [46]

decay time, due to sudden disappearance of matter behind the black hole horizon, can be explained in this scenario in a self consistent manner.[46] If this interpretation is correct then this provides strong observational evidence for the existence of stellar mass black hole in GRS 1915 + 105.

The X-ray Pulsars : Several X-ray pulsars including 4U 1907+09, Vela X-1, GX 1+4, Cep X-4 etc. have been observed with the IXAE during the last one and a half year. Pulsations with 435s period were clearly detected in the PPC data when this source was observed during an outburst. The intensity of this pulsar has varied in an erratic manner during our observations. Further analysis of the data is in progress. Strong and clear pulsed variations from the 283 s pulsar Vela X-1 were also detected. Timing analysis of the data is in progress to study the energy dependence of the pulse shape and the pulse fraction. The GX 1+4 observations were made when the source was in a faint state and the pulse fraction was low. The timing and spectral analysis of the PPC data on these and other pulsars is expected to provide significant new information about the astrophysical processes in these objects.

Conclusions

The space based observations, mainly from the satellite-borne instruments, have resulted in many new and interesting discoveries in X-ray astronomy in the last two and a half decades. These have greatly advanced our knowledge about the high energy processes responsible for production of X-rays in a variety of celestial sources. The study of X-ray binaries has developed into a major frontier area of research in high energy astrophysics. Detailed temporal and spectral investigations of the X-ray binaries have provided insight into the behavior of matter under extreme conditions which prevail in and near the vicinity of neutron stars and black holes in these sources. These studies have also given a big impetus to the theoretical understanding of the neutron stars and black holes in isolation as well as in the binary environment and the radiation processes at work in them. The whole field of accretion physics opened up with the realization that the release of gravitational energy by accretion of matter only can explain the energetics of the X-ray binaries.

There are still several puzzles and challenges in the field of X-ray binaries which hopefully will be resolved with further high resolution timing and spectral observations.

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