STUDIES IN X-RAY ASTRONOMY

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by

DHARMA PAL SHARMA
PHYSICAL RESEARCH LABORATORY
AHMEDABAD - 380009
INDIA

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TO THE MEMORY OF

MY BROTHER

LATE SHRI SATYA PAL

STATEMENT

Realising the advantage of conducting experiments near the magnetic equator due to the presence of very low charged particle background, the X-ray astronomy group at the Physical Research Laboratory, Ahmedabad planned a comprehensive programme in this field. The author as member of the X-ray astronomy group under Prof.U.R. Rao has been deeply involved in the design and fabrication of both balloon and rocket borne payloads for conducting these experiments, and in the analysis of the data obtained. This thesis presents a comprehensive account of the results obtained by the author and their interpretation.

For the rocket borne payloads Xenon-methane proportional counters with slat collimators have been extensively used. Most of the rocket experiments conducted so far from the Thumba Equatorial Rocket Launching Station (TERLS), Trivandrum ($\phi = 8^{\circ}$ 32'N, $\lambda = 76^{\circ}$ 51'E) have mainly concentrated in the 2-20 keV range. Consequently gas filled counters with 50-100 micron thick window of Beryllium were used as detectors. In addition balloon experiments have also been conducted from a low latitude station - Hyderabad ($\phi \approx 17^{\circ}$N), using 3 million cubic feet balloons. For all these experiments sodium iodide crystals were used as the main detectors, with plastic scintillator anticoincidence shield along with lead, tin and copper-graded shield. The balloon borne detectors were mounted on oriented platforms so that the tracking of the pre-selected stars for periods longer than an hour could be achieved with a pointing accuracy better than 1.5°.

The main body of the thesis deals with the study of variable X-ray stars and their detection through rocket borne, balloon borne and ground based techniques. The first chapter briefly reviews the important observational results on some of the important variable sources. The second chapter contains a detailed description of the rocket experiment and the results obtained therefrom. In the third chapter we have described the three balloon experiments and the results obtained during these observations. Fourth chapter contains the method and discussion of monitoring the X-ray sources using ground based techniques, through the ionization produced by their radiation in the night time D-region of the ionosphere. Additional material such as the optimal suitability of low latitude stations for conducting X-ray astronomy experiments and the methods of analysis are briefly described in the appendices.

The rocket borne instrumentation was mainly used to study the spectacular flare star Cen X-4 and the irregular variable Nor X-2. Besides these, useful information on the cosmic X-ray background has also been obtained. The important results which have come out of the present study are summarized below.

1) RESULTS ON CEN X-4:

a) The most significant feature of these sources is that they erupt into sudden brightness, reach a maximum in a few days and then decay more or less exponentially over a period of months.

b) The general behaviour of such sources is quite comparable to that of optical novae. Short period fluctuations are found to be superimposed on the smooth decay profile as in the case of optical novae. Similarly, the X-ray novae also show a definitive relationship between their peak emission and their decay time, the higher the intensity at the peak the lower is the decay time.

c) The energy released in the X-ray region during these explosions is very high, usually comparable or more than the emission from the strongest X-ray source Sco X-1 ($\approx 2 \times 10^{-7}$ ergs.cm^{-2}.sec^{-1}) in the 2-20 keV energy band.

d) All the sources of this type seem to exhibit basically an exponential spectrum with a temperature of $\approx 10^{7}$ ^{o}K corresponding to the peak of their intensity.

2. RESULTS ON NOR X-2:

a) The flux in the X-ray band of 2-18 keV follows an exponential spectrum having a plasma temperature of kT = 5.25 keV corresponding to T = 6×10^{7} ^{o}K. The flux received in the 2-10 keV energy range is $\approx 1.75 \times 10^{-8}$ ergs.cm^{-2}.sec^{-1}.

b) The source spectrum as well as the intensity show large variability whereas the X-ray flux changes by factors as large as 6, the temperature of the emitting region in the source derived under the assumption of an exponential spectrum also shows variations from kT = 4 keV to kT = 11 keV.

The study on background cosmic X-rays was made during two rocket flights in the energy range 2-18 keV. The cosmic background has been evaluated for the first time using earth as the occulting body. The spectrum derived in the 2-18 keV range from the present measurement is found to obey a power law spectrum with an index of $\alpha \approx 1 - 1.73 \pm .15$ having an average integrated flux of $\approx 10^{-8}$ ergs.cm^{-2}.sec^{-1}.sr^{-1}. in the 2-10 keV range. The results have indicated the effectiveness of the method using earth as a shutter, for deriving the diffuse background flux particularly in the energy band 2-30 keV and at low latitudes. With larger area counters in conjunction with secondary background rejection techniques such as the veto counters and pulse shape discrimination, this method can be very powerful tool for obtaining an accurate estimation of the diffuse cosmic X-ray background spectrum.

The balloon borne observations have been conducted mainly to study binary stars Cyg X-1 and Her X-1 in the hard X-ray region. The experiments conducted by the author provided the first evidence for the emission of the Her X-1 source at energies > 40 keV during ON state. Subsequently the same source was also monitored during the OFF state. The main results obtained by the author are summarized below.

1) RESULTS ON HER X-1:

a) The spectrum of the source above 20 keV obeys a power law with a spectral index of $\alpha \approx -2.05 \pm .33$. The observations clearly show that the spectrum in this range ($20 < E < 100$ keV) steepens considerably compared to the spectrum observed below 20 keV ($\alpha \approx -1.0$). The average integrated flux of X-rays in the energy range 20-100 keV observed during the ON state is $\approx 2.77 \times 10^{-10}$ ergs.cm^{-2}.sec^{-1}.

b) The present results along with the other observations show that the emission in the hard X-ray region also fluctuates considerably depending on the phase of 1.7 day orbital period as well as the epoch in the ON state of 35 day period.

c) No emission during the OFF state of the source was detected. The upper limits derived were $\leq 1.44 \times 10^{-10}$ ergs.cm^{-2}.sec^{-1}. Thus the intensity in the ON state is atleast a factor of ~ 2 greater than its intensity in the OFF state.

d) The arguments presented in the main body of the thesis show that the X-ray emitting source in Her X-1 should be a neutron star with its magnetic field axis not coinciding with the rotational axis and neutron star being a member of a close binary system.

2. RESULTS ON CYG X-1:

a) The observations indicate that the source has two distinct levels of emission one corresponding to the 'quiet' condition and the other to the 'flare' condition.

b) During the quiet condition the spectrum of the source can be fitted with a power law of index $\alpha \approx -1.9$ with an average integrated intensity in 20-100 keV amounting to $\approx 1.8 \times 10^{-8}$ $erg.cm^{-2}.sec^{-1}$. Even though the spectral behaviour seems to be almost same over long periods of time, the level of intensity of emission shows considerable long term variation by factors as large as ≈ 4.

c) During the flaring condition, the flux from the source is enhanced by factors of ~ 2.0 for a short duration of time (~ 10 mts) after which the level returns back to the pre-flare condition. The spectrum of the source during the flare hardens considerably and can be fitted with a power law spectrum having an index of $\alpha = -1.0$ with average integrated intensity of $\approx 2.86 \times 10^{-8}$ $ergs.cm^{-2}.sec^{-1}$ in 20-100 keV range.

d) The results of present flight which is substantiated by subsequent observations of other experimenters show that the flaring occurs for $\sim 10\%$ of the observation time usually coincident with the maximum emission of light during its binary cycle. Similarly, the enhancement of flux during the flare in the higher energy channels seems to precede the enhancement of the lower energy channels by as much as 5 minutes.

e) The arguments presented in the thesis show that the X-ray emission of this source is due to accretion of matter on to a black hole from its binary companion in a close binary system.

Recently it has become evident from the work carried out at PRL and elsewhere that ground based ionospheric techniques can be very useful to monitor the presence of X-ray stars. The main observations are centered on Sco X-1 and Tau X-1 whose effect on enhancing the ionization in the night time D-region has been unambiguously identified. In the present thesis we evaluate the importance of the potentiality of the method both from theoretical and from experimental point of view. In addition, the thesis also provides evidence to establish the nova like character of one of the X-ray stars for which (Cet X-2) very meagre observational data is available. Finally the possible effects of the recently discovered gamma ray bursts on the night time D-region of the ionosphere and their possible detection has been critically discussed. The most important results obtained by the author on this topic are summarized below:

a) Evidence is quite strong both from observational and theoretical standpoint for the detection of ionospheric effect due to strong celestial X-ray sources. Presently available evidence shows that the contribution to night time ionization of equatorial D-region ionosphere from cosmic X-rays, cosmic rays and Lyα are comparable with each other. There is also reasonable agreement between the theoretically expected nature of the effect and the experimental observations of VLF propagation.

b) The effect of these sources persists for about 2-3 hours on either side of the time corresponding to the peak effect, the extent of the spread depending upon the declination of the source. The investigation shows that the ionosphere behaves as a X-ray telescope with a large opening angle so far as the transit of celestial sources is concerned.

c) In general, since the contribution from Lyα can become significant during disturbed periods, the effect of celestial X-ray sources should be more frequently observed during solar quiet periods.

d) On an average basis, it should be possible to study systematic long term variations of the intensity of strong X-ray sources, in the time scales of a few months to a few years, using the data on VLF propagation.

e) There now exists a real possibility for the detection of such rare celestial events as flaring X-ray stars or super novae through their transient ionospheric effects using ground based VLF observations.

f) Owing to the fact that NO (Nitric Oxide) is very important minor constituent at D-region altitudes for deciding the ambient electron density, accurate knowledge of its altitude ion-concentration profile is very vital. The present work shows that the detectability of X-ray sources implies a concentration of NO atleast a factor of 7-10 lower than that determined by direct experiments.

(U.R.RAO)
Professor-in-Charge

DPSharma
(D.P.SHARMA)

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DPSharma

(D. P. SHARMA)

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