

Study of Temporal and Spectral Properties of X-ray Pulsars

Thesis

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by

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This is to certify that the thesis entitled “**STUDY OF TEMPORAL AND SPECTRAL PROPERTIES OF X-RAY PULSARS**” submitted to Vidyasagar University, Midnapore, West Bengal, India by **Mr. Manoj Mandal** (Registration No.- 955/Ph.D. (Sc) w.e.f. 09.12.2022.), for the award of the degree of Doctor of Philosophy (Science), is the result of original research work carried out by him under my supervision and guidance. Further, it is also certified that the thesis has not been previously submitted partly or fully for the award of any other degree or diploma to this University or any other institution. Mr. Manoj Mandal has fulfilled all the conditions required for the submission of the thesis under the rules of Vidyasagar University. In my opinion, the thesis has reached the standard of fulfilling the requirements of the University regulations relating to the award of the degree of Doctor of Philosophy.

I, also declare that this thesis is written based on the published articles in the internationally reputed journals of Astrophysics, and to my knowledge, the candidate has duly acknowledged all the sources that have been used to write the thesis.



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ABSTRACT

The accreting X-ray pulsars are binary systems that have an optical counterpart and a revolving, highly magnetized neutron star. The expelled plasma from the companion star accretes onto the compact object, resulting in pulsed X-ray emission. These sources are thought of as the only astrophysical laboratories capable of probing the properties of matter in extreme conditions, including strong magnetic fields (10^{12} G), high pressure, and extreme density. Considerable progress has been made in understanding these objects, both in terms of their constituent binary components and the features of their X-ray emission. However, further research is required to address many unresolved aspects, both theoretically and through observation. Some of the significant open aspects are the emission mechanism, the accretion structure's geometry and beaming pattern, and the impact of the optical counterpart on the measured X-ray properties. Matter accreted from the optical companion interacts with the high magnetic field of the neutron star during the accretion process, following field lines to hot magnetic poles located beyond the magnetospheric radius. It is thought that an accretion column, a structure resembling a column, will develop on top of a neutron star that is home to multiple intricate processes responsible for X-ray emissions.

This work presents the observational study of these processes for several X-ray pulsars driven by accretion. The luminosity and energy dependence of pulse profiles are used to study the beam function or geometry of the emission zone. Through pulse profile studies, the impact of the surrounding medium on the radiation released is also investigated. Comprehensive broadband spectroscopy of pulsars can yield valuable insights into the physical mechanisms driving radiation emission, as well as the distinctive characteristics of the matter distribution in the high-mass companion star's accretion column, accretion stream, accretion disk, photosphere, and stellar wind. The pulsar spectra can only be explained by a few more spectral components in addition to the continuum spectra. In addition, fluorescence emission lines were also observed from matter scattered about the neutron star. Pulsar spectra exhibit absorption lines, known as cyclotron lines, which are a crucial consequence of the interaction between the magnetic field and electrons. A more precise and direct measurement of the pulsars' magnetic fields can be obtained by detecting these lines.

A thermonuclear burst is used to probe the different fundamental properties of a neutron star. The unstable fuel burning on the neutron star's surface during a thermonuclear burst is the main reason for the sudden increase in X-ray intensity. The surface emission is more than ten times higher than the persistent emission during a Type-I burst. It can be used to distinguish between surface emission and total emission, which can be helpful in accurately calculating the different characteristics of a neutron star. The gas that powers the X-ray burst is accreted via an accretion disk by a neutron star from a low-mass companion star. The low-mass binary companion's materials accumulate on the stellar surfaces of the neutron stars. We have detected multiple thermonuclear X-ray bursts from the millisecond pulsar MAXI J1816–195. The detailed timing and spectral properties are studied during the burst. Different fundamental parameters, such as the apparent emitting area, source distance, burst fluence, and mass accretion rate, are also estimated from the spectral study. One of the main objectives is to understand the mechanism of such types of thermonuclear flashes.

Using space-based observatories like *NICER*, *Swift*, and *NuSTAR*, timing and spectral studies have been carried out in this work of several X-ray pulsars such as 1A 0535+262, RX J0440.9+4431, MAXI J1816–195, 2S 1417–624, and 2S 1553–542. The luminosity and energy dependence of pulse profiles and pulse fraction were also investigated in Be/X-ray binary pulsars to understand the accretion mechanism and beaming patterns. Above a certain luminosity (known as critical luminosity), the timing and spectral properties evolved significantly. The accretion mode, beaming patterns, and emission mechanism evolved significantly above this luminosity. Giant outbursts were reported for two X-ray pulsars, 1A 0535+262 and RX J0440.9+4431, which were used to probe neutron star properties at such a high luminosity, which was not observed earlier. A significant evolution of temporal and spectral properties is observed during the state transition. The critical luminosity is used to estimate the magnetic field for these supercritical X-ray pulsars. For the X-ray pulsar 1A 0535+262, a giant outburst of a record-high flux of 11 Crab was detected. The combined spectro-timing study indicated a state transition from the subcritical to supercritical accretion regime during the giant outburst. A significant evolution in spectral and temporal properties was observed during the giant outburst. The Cyclotron Resonant Scattering Feature (CRSF) originates from the resonant scattering of continuum photons with electrons, resulting in

an absorption-like feature in the energy spectra. The cyclotron line energy can be used to directly measure the magnetic field of the neutron star. The CRSF was detected from 1A 0535+262 during the 2020 outburst, and the magnetic field was estimated using the cyclotron line energy. The variation of the cyclotron line is probed to identify the spectral state. A significant evolution of line energy with luminosity was observed, which may be linked to the transition state in X-ray pulsars.

Keywords: X-ray binaries, Neutron stars, Accretion, Accretion disks, Accretion powered pulsars, X-ray pulsars timing, Spectroscopy, Cyclotron resonant scattering features, Magnetic fields, X-ray bursts, High energy astrophysical phenomena

DECLARATION BY THE CANDIDATE

I hereby declare that the thesis entitled “**STUDY OF TEMPORAL AND SPECTRAL PROPERTIES OF X-RAY PULSARS**” submitted for the degree of Doctor of Philosophy (Science) is my original work carried out by me under the supervision of Dr. Sabyasachi Pal, Associate Professor, Department of Pure and Applied Sciences, Midnapore City College, Midnapore, West Bengal.

I also declare that this work has not been previously presented, partly or fully, for any other degree to this University or any other institution. I have carefully acknowledged all the sources used in writing the thesis. I also declare that this thesis is based on my published articles in reputable international journals of Astrophysics.

The presented work in Chapter 3 is written based on three published articles in the *Monthly Notices of the Royal Astronomical Society* (Mandal et al., 2023c), *Astrophysics and Space Science* (Mandal & Pal, 2022b), *Journal of Astrophysics and Astronomy* (Mandal & Pal, 2023a). The work presented in Chapter 4 has been published in the *Monthly Notices of the Royal Astronomical Society* (Mandal et al., 2023b). Chapter 5 is written based on a published article in the *Monthly Notices of the Royal Astronomical Society* (Mandal & Pal, 2022a).

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