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Discovery of kHz Fluctuations in Centaurus X-3: Evidence for Photon Bubble Oscillations (PBO) and Turbulence in a High Mass X-ray Binary Pulsar

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We report the discovery of kHz fluctuations, including quasi-periodic oscillations (QPO) at $\sim330~$Hz and $\sim760~$Hz and a broadband kHz continuum in the power density spectrum of the high mass X-ray binary pulsar Centaurus X-3 (Jernigan, Klein and Arons 2000). These observations of Cen X-3 were carried out with the Rossi X-ray Timing Explorer (RXTE). The fluctuation spectrum is flat from mHz to a few Hz, then steepens to f^{-2} behavior between a few Hz and ~ 100 Hz. Above a hundred Hz, the spectrum shows the QPO features, plus a flat continuum extending to $\sim1200~$Hz and then falling out to $\sim1800~$Hz.

Multi-dimensional radiation hydrodynamics simulations of optically thick plasma flow onto a magnetized neutron star show that the fluctuations at frequencies above 100 Hz are the likely consequence of the photon bubble turbulence and oscillations (PBO) previously predicted (Klein et al. 1996) to be observable in this source. We show that previous observations of Cen X-3 constrain the models to depend on only one parameter, the size of the polar cap. For a polar cap opening angle of 0.25 radians (polar cap radius ~ 2.5 km and area ~ 20 km^2, for a neutron star radius of 10 km), we show that the spectral form above 100 Hz is reproduced by the simulations, including the frequencies of the QPO and the relative power in the QPO and the kHz continuum. This has resulted in the first measurement of the polar cap size of an X-ray pulsar.

X-ray pulsar: Binary X-ray source: QPO: radiation hydrodynamics

Introduction

The binary system composed of the neutron star Cen X-3 and its companion O-type supergiant has been studied extensively by all orbiting X-ray astronomy observatories. The results from the Uhuru satellite identified the system as an eclipsing binary X-ray pulsar with a 2.087 day orbit and a 4.84 s pulse period. The well determined distance to the binary system yields in accurate determination of the luminosity $L_{x}\simeq 9.4~\times~10^{37} {\rm erg~s^{-1}}$. Recently a cyclotron feature was detected in the X-ray spectrum of Cen X-3 providing precise knowledge of its surface magnetic field strength $B \simeq 3.2~\times~10^{12} {\rm Gauss}$.

Motivated by earlier predictions of the likelihood of the existence of Photon Bubble Oscillations (PBO) in Cen X-3 (Klein et a. 1996), we have analyzed two consecutive binary cycles of the source to search for PBO. We have also calculated new theoretical models constrained by the observable parameters of Cen X-3. The physics describing the radiation hydrodynamics which governs the accretion of matter onto the highly magnetized polar caps of luminous X-ray pulsars has been described elsewhere (Arons, Klein and Lea 1987; Klein and Arons 1989). Early numerical results (Klein and Arons 1991) and linear stability analysis (Arons 1992) suggested the formation of small scale but large amplitude fluctuations in the matter density and velocity, which form radiation filled pockets almost devoid of plasma (``photon bubbles''). These photon bubbles (PB) result in significant observable fluctuations in the emitted luminosity.

We observed the X-ray emission from Cen X-3 with the RXTE over two binary cycles and clearly detect both kHz QPO and a broadband kHz continuum in the power density spectrum which we identify with PBO and the high frequency power law continuum generated by photon bubble ``turbulence''. The {\it only} remaining free parameter in our numerical models is the size of the polar cap. We show that by adopting a reasonable size for the polar cap of Cen X-3, we are able to semi-quantitatively match the frequencies of two observed QPO/PBO peaks and the kHz continuum with the power density spectrum of our calculated radiation-hydrodynamic models; thus giving strong evidence for the existence of PBO and photon bubble turbulence in Cen X-3.

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Observations

Separate continuous observations of Cen X-3 were carried out with the PCA on-board RXTE for two consecutive binary cycles. Figure 1 is a log--log presentation of the average deadtime corrected power density spectrum for the entire data train of the low energy channel (1--7 keV). Note the smooth plateau at very low frequencies ($10^{-2}-10^{-1}~$Hz) followed by the first and second harmonics of the 4.8 s pulse ($10^{-1}-10^0~$Hz). The periodic pulse and its harmonics are superimposed on a broadband power law which falls from an amplitude of $\sim10^{-1}$ to 10^{-6} with a slope of approximately -2 (see dashed line). At about $100~$Hz another power density plateau appears, followed by two QPO peaks (~331 and $\sim761~$Hz). These two QPO peaks (50\% confidence ranges $260-407~$Hz and $671-849~$Hz) are superimposed on the power density plateau which falls sharply at frequencies above $\sim1200~$Hz. The curve falls to a level of about $10^{-7}\left({\rm rms \over mean}\right)^2~{\rm Hz}^{-1}$ at $\sim1800~$Hz which has reached the Poisson detection limit of the transform.

Theoretical Model and Results

We calculate a model appropriate for the surface conditions of the neutron star Cen X-3 as the self-consistent solution of the full two-dimensional, time-dependent equations of the radiation hydrodynamics.

Figure 2. shows the results for the power density spectra of the time series of the emergent transverse luminosity out of the sides of the accretion column for three models (A, B and C) for which the values L_{x} and B have been set to those measured for Cen X-3. The models A, B and C are distinguished by setting the polar cap size to 0.25, 0.3 and 0.4 radians respectively. Model A ($\theta_c = 0.25$ radians) shows PBO at 350 Hz and a composite PBO at about 700 Hz. The frequencies of these PBO are in good agreement with frequencies of the QPO peaks observed in the power density spectrum. The approximate balance between PBO/QPOs and continuum is also roughly true for all three theoretical models. The additional strong broad composite PBO at $\sim3000~$Hz that is seen in models A and B is not seen in the observed power density spectrum of Cen X-3. However it is below the level that could be easily detected with the PCA. The only free parameter in our calculations is the size of the polar cap. If we consider the whole picture these models taken together determine a range for the polar cap radius of $\sim$2--3 km.

Conclusions

We have advanced the view that the fluctuations observed in the power spectrum at frequencies exceeding a few hundred Hz have their origin in the intrinsic photon bubble instability of the accretion flow at the stellar surface. Prior to the RXTE launch we predicted the observation of photon bubble phenomena including the specific existence of kHz fluctuations and some power in quasi-periodic oscillations identifiable as PBO in Cen X-3 (Klein et al. 1996). We have now observed these fluctuations in Cen X-3. A careful comparison of the predicted power density from the PB simulations with the observed power density spectrum constrains the size of the polar caps of Cen X-3 to a radius of $\sim$2--3 km. This has permitted the first model-dependent measurement of the size of the accreting polar cap in an X-ray pulsar.

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