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ON THE OBSERVABILITY OF MICROSECOND TEMPORAL STRUCTURE IN THE EMISSION FROM X-RAY BINARY PULSARS

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ABSTRACT

We discuss the possibility of detecting the microsecond granularity expected in the flux from wind-fed X-ray binary pulsars. This microsecond structure is predicted by the noisy accretion scenario; we derive the physical characteristics of such burst structure in the framework of this model. We investigate the temporal dispersion induced by the scattering of burst photons in their passage through the neutron star magnetosphere and conclude that microsecond structure could indeed be observable for energies less than the cyclotron energy. We show that the coincidence timing mode for the Proportional Counter Array on-board *XTE* can be used very effectively to statistically discriminate these microsecond bursts from accidental spurious detections.

Subject headings: accretion, accretion disks — pulsars: general — stars: neutron — X-rays: stars

1. INTRODUCTION

The physics of accretion in X-ray binary pulsars has been characterized by two fundamental assumptions on the accretion rate: homogeneity and stationarity. While these two constraints greatly simplify the mathematical treatment of the problem, they are far from being applicable to the class of objects we are interested in. Indeed, phenomena of flaring activity and inhomogeneity in the stellar wind, which can be associated with variability in the accretion rate, are very common in wind-fed pulsars (Nagase 1989).

Furthermore, the observation of a random behavior of spin-up and spin-down episodes in the pulse period history of wind-fed pulsars is not understood in the framework of a homogeneous accretion rate. In order to explain spin-down episodes, gradients in both velocity and density in the stellar wind have been invoked (Wang 1981). Numerical simulations have also shown that, even in the case of an accretion flow that is uniform in density, temperature, and velocity, the accretion rate onto the neutron star will not be steady, but will show instabilities at the accretion radius which are intrinsic to the accretion flow itself (Matsuda et al. 1991). These instabilities manifest themselves as a flip-flop behavior, which could be responsible for the fluctuations in the rotation rate of these sources. An initial, simplified attempt to analytically describe this behavior is discussed by Livio et al. (1991), who find that the Bondi-Hoyle accretion theory could allow nonlinear phenomena and instabilities even in the case of homogeneous accretion flows.

In this framework it is easy to understand the need of some nonstationary, nonhomogeneous model of wind accretion. And indeed, it is possible to find in the literature numerous models for nonhomogeneous accretion onto neutron stars (Arons & Lea 1980; Hameury, Bonazzola, & Heyvaerts 1980; Morfill et al. 1984; Demmel, Morfill, & Atmanspacher 1990) essentially developed for explaining the super Eddington luminosity observed in some X-ray pulsars (see, e.g., Nagase 1989). The "noisy accretion" model by Orlandini & Morfill (1992) was introduced to explain some peculiarity observed in the frequency power spectra of the X-ray binary pulsar GX 301−2. In this model (which we will use in this paper) a "granularity" in the emission process is introduced due to the instability which occurs at the magnetospheric limit; such granularity manifests itself with timescales on the order of a microsecond. While likely Kelvin-Helmholtz instabilities related to torque noise in disk-fed accretion (Kundt, Özel, & Ercan 1987; Baykal & Ögelman 1993) may indeed lead to some kind of granularity in the emission from such sources as well, the model we address here is not appropriate for estimating the characteristics of the specific temporal behavior to be expected in this case.

We begin with a description in § 2 of the noisy accretion model in wind-fed X-ray binary pulsars and investigate in § 3 the temporal broadening of the micropulses during their passage through the neutron star magnetosphere. Finally, in § 4 we discuss the feasibility for the detection of the associated granular emission by means of the Proportional Counter Array (PCA) and its data system on-board the *X-ray Timing Explorer* (*XTE*) mission, scheduled to be launched in 1995 (Bradt, Rothschild, & Swank 1993).

2. THE PHYSICAL MODEL

The physics of wind-fed X-ray binary pulsars can be best described if we subdivide the system in three different regions, in which the magnetospheric radius acts as the separator: "beyond," "onto," and "inside" the magnetospheric radius r_m. The physical processes which occur in these regions are different, and the timescales associated with them are different, too.

In the region "beyond" r_m, the flow of plasma is driven by the radiative force from the optical star (wind-fed binaries are powered by stellar wind from early-type stars, typically of spectral type O–B). The characteristic timescale we expect for processes occurring in this region is of the order of 100–1000 s or more, the dynamical timescale for distances of the order of millions of km and wind velocities of the order of hundreds/thousands km s^{-1}.

At the magnetospheric limit we have that the physics involved is the magnetohydrodynamical instability (both

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Rayleigh-Taylor and Kelvin-Helmholtz) which allows matter to penetrate the magnetosphere and therefore accretion to occur. The physical processes involved in this region have timescales of the order of 0.1–10 s (growth time for the instabilities).

At the neutron star surface, on the other hand, we expect time scales that are much shorter, because the physical processes involved are Compton cooling and heating, bremsstrahlung, and Coulomb interactions. Timescales as short as a microsecond or less can be achieved only for processes which occur at the neutron star surface. Therefore, a microstructure in the emission can be associated only with processes which occur close to the magnetic polar caps of the neutron star. Clearly, as emphasized by L. Ozernoi (personal communication), such microsecond granularity in X-ray radiation cannot occur for those binaries in which the compact object is a black hole.

In the noisy accretion model, the stellar wind coming from the optical companion of the neutron star is captured by its intense gravitational field and accreted. The strong magnetic field halts the incoming matter at a distance on the order of $r_m \approx 10^8$ cm from the neutron star surface. Here matter enters the magnetosphere by means of Rayleigh-Taylor instability, in the form of accreting blobs. The theory by Arons & Lea (1976a, b; 1980) can describe the physical parameters of these blobs as radius, density, and temperature, in terms of quantities such as the X-ray luminosity, the neutron star mass, and the magnetic field strength.

During their radial infall toward the neutron star surface, the blobs decrease their radius because of Compton cooling. At a distance called plasmapause (of the order of 10^7 cm) they are channeled by the magnetic field lines toward the neutron star polar caps; their physical properties remain "frozen" during their fall. The detailed analysis presented by Morfill et al. (1984) of what then occurs near the surface of the neutron star has provided the basis for our discussion.

When these blobs arrive onto the magnetic polar caps, they release their kinetic energy into X-ray radiation which, after interacting with the strongly magnetized plasma, reaches the observer. We have therefore a "granularity" in the emission process due to the inhomogeneous accretion onto the neutron star.

In order to estimate the temporal structure of the X-ray emission due to the infalling blobs, we will estimate the duration of a single burst both from a dynamical point of view and a thermal point of view. In the former case, the dynamical time scale which an unstable blob takes to be completely squashed onto the neutron star (in other terms, the duration of a shot in a shot noise process) is

$$\tau_{\rm sq} \equiv \frac{2}{3}\frac{r_x}{v_b(r_x)}\left\{\left[\frac{r_x + 2r_b(r_x)}{r_x}\right]^{3/2} - 1\right\} \tag{1}$$

(Morfill et al. 1984), where r_x is the neutron star radius, and $v_b(r_x)$ and $r_b(r_x)$ are the (free-fall) velocity of the unstable blob at the neutron star surface and its radius, given by

$$r_b(r) \approx 2.5 \times 10^7 \mu_{30}^{2/5} L_{37}^{-6/5} m^{6/5}\left(\frac{r}{r_m}\right)^2 \tag{2}$$

(Arons & Lea 1980; Orlandini & Morfill 1992). Here μ_{30} is the magnetic moment of the neutron star in units of 10^{30} gauss cm^3, L_{37} is the X-ray luminosity in units of 10^{37} ergs s^{-1}, and m is the neutron star mass in solar mass units. The numerical value of $\tau_{\rm sq}$ for a typical neutron star, for two values of the X-ray luminosity is

$$\tau_{\rm sq} = \begin{cases} 1.2 \times 10^{-5}\ \text{s}\,, & L_{37} = 0.1\,; \\ 7.3 \times 10^{-7}\ \text{s}\,, & L_{37} = 1\,. \end{cases} \tag{3}$$

The duration of the "squashing" process of a blob depends on the way in which the kinetic energy of the infalling blob is converted into radiation. The timescale of conversion is determined by the transfer of momentum from the ions to the electrons, τ_{i-e}, and by the photon production rate in the interaction of the electrons with the matter and the magnetic field, $\tau_{\rm ph}$. For a typical plasma of density 10^{26} cm^{-3} and electron temperature of 30 keV, they are

$$\tau_{i-e} \approx 3 \times 10^{-12}\ \text{s}\,; \quad \tau_{\rm ph} \approx 2 \times 10^{-8}\ \text{s} \tag{4}$$

(Morfill et al. 1984).

After a time $\tau_{\rm ph}$ (the more relevant of the two) a deceleration front starts to move upward through the blob, i.e., the X-rays start to "diffuse" into the blob.

In the case of no radiation escaping from the sides of the blob, the front moves at a constant velocity roughly equal to the free-fall velocity. In the more realistic case of radiation loss, this velocity is smaller. The height h of the front as a function of time is given by

$$h(t) = 7 \times 10^{-11} v_b \rho_b r_b^2\left[1 - \exp\left(-\frac{10^{11}t}{7\rho_b r_b^2}\right)\right] \tag{5}$$

(Morfill et al. 1984), where v_b, r_b, and ρ_b are computed at the neutron star surface. From this expression we can see that the deceleration front will emerge from the blob after a time $\tau_{\rm df}$

$$\tau_{\rm df} \approx \begin{cases} 7 \times 10^{-6}\ \text{s}\,, & L_{37} = 0.1\,; \\ 5 \times 10^{-7}\ \text{s}\,, & L_{37} = 1\,. \end{cases} \tag{6}$$

This timescale is of the same order of magnitude as the dynamical timescale previously computed (see eq. [3]); both of these considerations predict microsecond structure in the emission from X-ray pulsars.

The other quantity we need in order to estimate the effect of this granularity on the observed flux is the average rate of shots per unit time, λ, which is

$$\lambda = \frac{1}{2}\frac{4\pi r_m^2}{\Lambda^2 \tau_{\rm RT}} \approx \begin{cases} 10\ \text{s}^{-1}\,, & L_{37} = 0.1\,; \\ 100\ \text{s}^{-1}\,, & L_{37} = 1 \end{cases} \tag{7}$$

(Orlandini & Morfill 1992), where $\tau_{\rm RT}$ is the characteristic timescale for the growth of the Rayleigh-Taylor instability, and Λ is the wavelength of the perturbation.

We now have all the information needed to quantitatively describe the bursting behavior of the X-ray emission. The luminosity during a single burst is

$$\mathscr{L}_b = \frac{\mathscr{L}_x}{\lambda \tau_{\rm sq}} \approx \begin{cases} 8.3 \times 10^{39}\ \text{ergs s}^{-1}\,, & L_{37} = 0.1\,; \\ 1.4 \times 10^{41}\ \text{ergs s}^{-1}\,, & L_{37} = 1\,, \end{cases} \tag{8}$$

i.e., the luminosity produced by each instability blob is super-Eddington (this is not surprising, because of the nonstationarity of the emission process). Under the assumption of black-body emission from the blob, this would correspond to temperatures between 10 and 100 keV for the two luminosity states, respectively.

3. ON THE OBSERVABILITY OF MICROSECOND BURSTING

As we have shown in the previous section, the noisy accretion scenario predicts microsecond structure in the emission from wind-fed X-ray binary pulsars. The passage of this radiation through the neutron star magnetosphere will tend to broaden the pulses. In order to quantitatively describe the amount of this broadening it is necessary to solve the transport equation, a challenging task beyond the scope of the present paper. Crude estimates indicate that this could be a severe problem. However, as described below, we have identified a tenable regime where the emerging radiation would preserve the microsecond temporal characteristics of the initial emission.

Considering the photons as independent particles undergoing multiple scattering in a plasma of uncorrelated electrons, their transit through a region of spatial thickness H can be considered a random walk when the optical depth κ exceeds unity. In such case the mean step-length is H/κ and the average number of steps $\mathcal{N}$ is given by $\mathcal{N} = \kappa^2$ for $\kappa \gg 1$. The rms deviation in the number of scatters is then given by rms $= (\mathcal{N})^{1/2} = \kappa$. So the rms spread in the transit time would be approximated by H/c, where c is the velocity of light. This means that the spread in transit time across a region could very well be comparable to what the transit time of that region would have been if there were no scattering.

The passage of the microsecond pulses through the neutron star magnetosphere, of scale height $r_m \approx 10^8$ cm, would cause a dispersion of the signal of the order of milliseconds, thereby smearing out the effect. However, the strong magnetic field of the neutron star has a pronounced effect on the Thomson scattering cross section. In particular, for photons moving in a direction parallel to that of the magnetic field, the quantum total cross section, $\sigma_{\rm tot}$, is strongly reduced in comparison with the classical Thomson value, $\sigma_{\rm Th}$, because of the transversality of the wave (Herold 1979)

$$\sigma_{\rm tot} \approx \sigma_{\rm Th}\left(\frac{E}{E_c}\right)^2 , \tag{9}$$

where E is the photon energy, and $E_c \equiv \hbar(eB/mc)$ is the cyclotron energy. Equation (9) is valid in the approximation $E \ll E_c$.

The relevance of equation (9) is that photons of energy much less than the cyclotron energy will have their scattering coefficient drastically reduced if emitted along the magnetic field lines. This occurs, for example, in the case of emission from a slab at the magnetic polar caps of the neutron star—the so-called pencil beam emission pattern, a situation typical of low-luminosity X-ray pulsars. For observations restricted to radiation within the pencil beam we consider those cases where the effective optical depth for scattering has been reduced to somewhat less than unity. Under such conditions, a substantial fraction [$\exp(-\kappa)$] of the initially emitted photons would emerge unscattered, thereby making feasible the measurement of microsecond granularity.

From the observed cyclotron resonance in the spectra of four X-ray binary pulsars (Makishima et al. 1990), we can say that for $E \lesssim 5$ keV, microsecond duration pulses from the surface of neutron stars such as those here represented should be detectable relatively undistorted.

4. FEASIBILITY FOR DETECTION OF MICROSECOND BURSTING

4.1. *Previous High-Temporal Resolution Observations*

Concerning archival data, the only high-throughput X-ray observatory that we are aware of which had potential timing performance better than 10 microseconds was the *HEAO 1* A-1 experiment. However, during the actual mission this capability was operative in a way that generally precluded that sort of multidetector coincidence mode of analysis discussed here.

Strong experimental limits on possible submillisecond granularity in the flux from an X-ray binary come from observations of Sco X-1, the brightest known source, although it is a low-mass binary fed via an accretion disk mechanism for which our model does not apply. In a high-temporal resolution rocket-borne observation of Sco X-1 (Boldt, Holt, & Serlemitsos 1971), the counts recorded in independent consecutive 0.3 millisecond samples were in fact found to be statistically consistent with the Poisson distribution expected for continuous emission. This indicated that submillisecond bursts of duration greater than 2.8 microseconds (the instrumental dead-time) could not constitute more than a few percent of the flux from Sco X-1. It is important to recognize, however, that this analysis did not address the particularly interesting possibility of bursts which are less than 2.8 microseconds in duration.

4.2. *X-Ray Timing Explorer*

The PCA of five independent co-aligned X-ray detectors on the *XTE* is particularly well suited for detecting possible microsecond temporal structure in the X-ray emission from observed sources, even faint ones. Detecting such microsecond bunching of photons with a single proportional counter alone would be prohibitively difficult. In particular, a 1 μs duration burst of multiple photon interactions all taking place in the *same* counter would tend to appear as a single "pileup" event or sometimes be vetoed. However, two or more such temporally correlated photon interactions, when distributed among *different* PCA detectors, could be readily identified as a genuine burst by means of microsecond coincidence timing among these independent PCA sensors. Such an easily implemented coincidence timing mode is available with the on-board PCA data system planned for *XTE*. It makes readily feasible the investigation of temporal structure for source emission in this previously unexplored microsecond regime. This has been experimentally verified for the PCA in our laboratory by noting that the recorded temporal jitter is less than 0.2 microseconds for the relative timing of detections in two separate *XTE* proportional counters for the simultaneous pair of 27 keV and 35 keV photons produced in the radioactive decay of ^{125}I (W. Zhang & K. Black, private communication).

For GX 301−2 (at 1.8 kpc) the expected counting rate in a single *XTE* proportional counter is $\sim 10^3 L_{37}$ per second. For estimating the limiting sensitivity of *XTE* for the detection of microbursts from such a source, however, we consider the more representative (albeit less favorable) hypothetical situation of an object like this that is about 3 times farther away (i.e., at about 6 kpc) within the galactic disk. The corresponding source count rate R_S in the composite PCA of five counters is then

$$R_S = 5 \times 10^2 L_{37}\ {\rm s}^{-1} . \tag{10}$$

We assume that a fraction f of source emission appears in the form of discernible bursts of microsecond duration and that these bursts occur randomly at a rate λ s^{-1}. The expectation value for the number of counts (n) in the PCA from a characteristic burst is then

$$n = fR_S/\lambda . \tag{11}$$

The probability P_B of ≥ 2 counts from a burst within the composite PCA of five detectors is given by

$$P_B = [1 - (n + 1) \exp(-n)] \, . \qquad (12)$$

The rate R_B of detecting genuine bursts by multiple detector coincidence (twofold or greater) is then

$$R_B \approx \lambda P_B = \lambda[1 - (n + 1) \exp(-n)] \, . \qquad (13)$$

Since the anticipated background (i.e., not due to X-rays from the source) is ~ 7 counts s^{-1} per detector (for an assumed 20 keV bandwidth), the total PCA count rate R_T to be considered here is

$$R_T \approx 5 \times 10^2 (L_{37} + 0.07) \ \text{s}^{-1} \, . \qquad (14)$$

For PCA counts randomly distributed in time, the probability P_A of ≥ 1 *accidental* count within one microsecond of a *given* count is

$$P_A = [1 - \exp(-2 \times 10^{-6} R_T)] \, . \qquad (15)$$

The corresponding rate R_A of spurious bursts arising from multiple detector accidental coincidence (twofold or greater) is then

$$\begin{aligned} R_A &\approx R_T P_A = R_T[1 - \exp(-2 \times 10^{-6} R_T)] \\ &\approx 2 \times 10^{-6} (R_T)^2 \quad \text{for } R_T \ll 10^6 \ \text{s}^{-1} \, . \end{aligned} \qquad (16)$$

To exhibit the sensitivity of the *XTE* PCA for detecting microsecond bursting we have calculated the rate R_B for genuine burst detections and the rate R_A of accidental spurious detections for cases characterized by values of L_{37}, λ, and f of particular interest (see Table 1). From the rates listed in this table we conclude that in fact the accidentals considered here are sufficiently small for allowing the clear detection of bursts. Even for the worst case (no. 3) characterized by a small granular component of 2%, the number of detected *events* (bursts plus accidentals) would be greater than the expected number of accidentals by a statistically significant amount after an exposure of only 100 s.

TABLE 1

XTE PCA SENSITIVITY TO MICROSECOND BURSTING

Case	L_{37}	λ (s^{-1})	f	R_S (s^{-1})	n	R_B (s^{-1})	R_A (s^{-1})
1.........	1	100	1	500	5	96	0.57
2.........	1	100	0.1	500	0.5	9.0	0.57
3.........	1	100	0.02	500	0.1	0.47	0.57
4.........	0.1	10	1	50	5	9.6	0.015
5.........	0.1	10	0.1	50	0.5	0.9	0.015

For cases 4 and 5 we note that bursts of longer duration (i.e., 10 microseconds) could well be more appropriate. In such a situation the accidental rate would increase by a factor of 10. However, even for the worst-case scenario considered in this regime (case 5) the average number of bursts detected in only a 10 s exposure would already be statistically significant. Hence, temporal granularity of the sort discussed here should be readily observable with a multidetector instrument such as the *XTE* PCA. An observed signal of this kind would provide a unique view of neutron star surface physics.

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