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ANOMALOUS PERIODICITY IN THE VERY HIGH ENERGY GAMMA-RAY SOURCES

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ABSTRACT

Evidence for anomalous periodicity in TeV γ-rays that is ~0.1% shorter than the X-ray period, has been observed from Her X-1. It is suggested that such periodicity may result from the interaction of a broad particle beam with target matter removed from the accretion disk by instabilities at the disk/magnetosphere interface. Such target matter will initially travel in a Keplerian orbit about the pulsar. Very high energy (VHE) γ-rays are observed only when the target matter is between the neutron star and the observer. As such, the γ-rays are observed to be pulsed at the period of the Keplerian orbit.

Subject headings: gamma rays general — radiation mechanisms — stars: individual (Her X-1)

I. INTRODUCTION

Recent studies of TeV γ-ray emission from Her X-1 have suggested periodicity significantly different from that of the rotating neutron star (Resvanis *et al.* 1988; Lamb *et al.* 1988; Dingus *et al.* 1988). Indeed, investigation of the previous period measurements from this object at TeV energies indicates that a large number of the observations are inconsistent with the neutron star rotation period as determined by X-ray measurements (Fig. 1). Because the duration of the episodes of emission in the very high energy (VHE) regime are often quite short ($T \sim 10^3$ s), the corresponding period resolution is fairly broad ($\Delta P \sim P^2/T$). Thus, it is conceivable that anomalous periodicity from other binary objects exists as well but that the effects have either not yet been resolved or have been overlooked by observers concentrating on the neutron star rotational period.

The mechanism responsible for the anomalous periodicity observed in Her X-1 may be similar in nature to that governing the behavior of the quasi-periodic oscillation (QPO) sources at optical and X-ray energies. Various QPO models have been suggested (for reviews, see Lamb 1986 and Lewin 1986), many of which assume the presence of accretion disk matter in a Keplerian orbit which is either self-luminous or which periodically obscures an emission region. In the case of VHE γ-ray production, such matter could serve as the site for conversion of energetic charged particles to γ-rays through π^0 decay. In § II we investigate instability regions at the magnetosphere/accretion disk interface as possible candidates for production of such target regions. In § III we suggest that a broad particle beam produced in the acceleration regions found in pulsar magnetospheres, in conjunction with target matter released from instabilities in the accretion disk and orbiting the neutron star with Keplerian velocities, can result in episodic emission of VHE γ-rays at periods differing from that of the rotating neutron star.

II. ACCRETION IN X-RAY BINARIES

X-ray binary objects are generally believed to be powered by the transfer of material from a companion star onto a neutron star. In many such systems, the matter is in the form of an accretion disk. The general properties of accretion disks have been reviewed by Pringle (1981) and Frank, King, and Raine (1985). Here we summarize the features pertinent to our discussion and introduce reasonable working values for numerical quantities associated with the Her X-1/HZ Her system.

The matter which comprises an accretion disk is characterized by highly subsonic radial velocities and supersonic tangential velocities. The structure of so-called α-disks is described by the Shakura-Sunyaev equations (Shakura and Sunyaev 1973). In particular, the disk thickness and density are given by (Frank *et al.* 1985)

$$H = 1.7 \times 10^8 \alpha^{-1/10} \dot{M}_{16}^{3/20} M_1^{-3/8} R_{10}^{9/8} f^{3/5} \text{ cm}$$

and

$$\rho = 3.1 \times 10^{-8} \alpha^{-7/10} \dot{M}_{16}^{11/20} M_1^{5/8} R_{10}^{-15/8} f^{11/5} \text{ g cm}^{-3} .$$

Here $\dot{M}_{16}$ is the accretion rate in units of 10^{16} g s^{-1}, M_1 is the mass of the accreting star in solar masses, R_{10} is the distance from the central object in units of 10^{10} cm, and

$$f = 1 - \left(\frac{R_s}{R}\right)^{1/2}$$

where R_s is the radius of the central compact object. The unknown quantity α is introduced to parameterize the turbulent viscosity in the disk and is less than ~1. Matter in the outer regions of the disk follow slowly decaying Keplerian orbits as angular momentum is lost due to viscous torques. The *corotation radius* of the system (i.e., the radius at which the period of the Keplerian orbit matches the rotation period of the neutron star) is given by

$$r_{\text{cor}} = \left(\frac{GM}{4\pi^2}\right)^{1/3} P^{2/3} ,$$

where M is the mass of the neutron star. The boundary of the neutron star magnetosphere is determined by the radius at which the magnetic stress on the disk plasma and the material stress associated with the radial drift and orbital motion of the accreting matter are equal. This boundary is given by (Ghosh and Lamb 1979*a*)

$$r_0 \approx 0.5 r_A ,$$

where

$$r_A = \mu^{4/7} (2GM)^{-1/7} \dot{M}^{-2/7}$$

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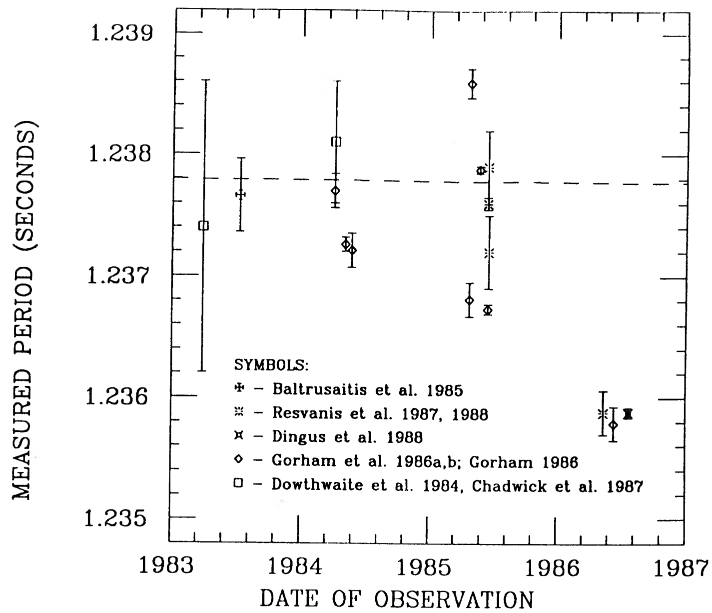

FIG. 1.—Distribution of measured periods for Her X-1 in TeV gamma-ray detections (Baltrusaitis *et al.* 1985; Resvanis *et al.* 1987, 1988; Dingus *et al.* 1988; Gorham *et al.* 1986*a*, *b*; Gorham 1986; Dowthwaite *et al.* 1984; Chadwick *et al.* 1987). The dashed line represents the neutron star rotational period as determined by X-ray measurements.

is the Alfvén radius. Here μ is the magnetic moment of the neutron star.

Ghosh and Lamb (1979*b*) note that, for systems such as Her X-1, r_0 is very near (but smaller than) the corotation radius r_{cor}. Given the ~ 1.24 s rotation period of Her X-1, we have $r_{cor} \approx 1.9 \times 10^8$ cm. The basic configuration of the inner regions of the accretion disk are shown schematically in Figure 2 while the relevant parameter values are listed in Table 1. The radius r_K which corresponds to a Keplerian orbit whose period (1.2359 s) is equal to that measured by Resvanis *et al.* (1988), Lamb *et al.* (1988), and Dingus *et al.* (1988) is very near, but somewhat ($\approx 0.1\%$) smaller than r_{cor}.

While the bulk of the material in the accretion disk orbits the central star with Keplerian velocities, in the region of the Alfvén radius the magnetic field strength becomes sufficient to dominate this pattern. As a result of instabilities due to relative motion of magnetospheric and disk matter, plasma at the surface of the inner regions of the disk may be channeled up out of the disk plane becoming locked into corotation on the magnetic field lines and, eventually, accreted onto the poles of the neutron star. The angular momentum transferred from the disk material to the neutron star though the magnetic field results in torques which act to spin-up the star. Ghosh and Lamb (1979*a*) have shown that, in the outer transition zone of the disk, spin-down torques also exist. The rate at which the rotation period changes is determined by the sum of these torques. While most systems display overall spin-up behavior, occasional spin-down episodes associated with low accretion rates are observed. Fluctuations in $\dot{P}$ can be explained by fluctuations in the accretion rate $\dot{M}$ and the flow geometry (Ghosh and Lamb 1979*b*; Ögelman 1987). Such fluctuations, however, are much too small in magnitude to explain the anomalous

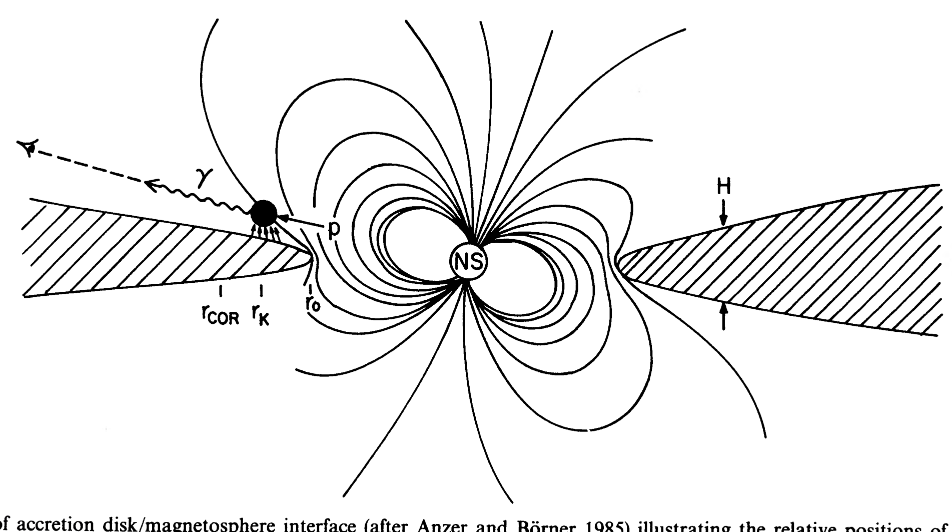

FIG. 2.—Schematic of accretion disk/magnetosphere interface (after Anzer and Börner 1985) illustrating the relative positions of r_0, r_K, and r_{cor} (*see text*). Matter in the vicinity of r_K is proposed as the conversion target for the production of VHE γ-rays from an energetic beam of protons.

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TABLE 1

ASSUMED HER X-1 SYSTEM PARAMETERS

Parameter	Value
Radius	10^6 cm
Mass	1.4 $M_\odot$
Period	1.24 s
Accretion rate	5×10^{16} g s^{-1}
r_{cor}	1.9×10^8 cm
$\rho(r_{cor})$	1.4×10^{-4} g cm^{-3}
$H(r_{cor})$	2.1×10^6 cm

periodicity observed in VHE γ-rays. Thus, it seems clear that it is *not* the period of the neutron star which is being measured in the VHE observations under consideration.

III. VHE γ-RAY PRODUCTION AT THE ACCRETION DISK/MAGNETOSPHERE INTERFACE

While various models exist which predict the presence of large accelerating fields in the vicinity of rotating magnetic neutron stars, there is presently no consensus as to the full details. This is especially true for systems in which an accretion disk strongly modifies the neutron star magnetosphere. Vestrand and Eichler (1982), for example, suggest pulsar acceleration of protons which, upon striking the outer atmosphere of the companion star, produce γ-rays through π^0 decay. We consider an acceleration region which is broad in angular extent, thus resulting in a broad beam of energetic protons. If a fixed conversion target lies between the observer and the neutron star (i.e., $v_\phi = 0$, $v_r \neq 0$), then one might expect a VHE γ-ray light curve whose duty fraction is determined by the angular extent of the acceleration region (as well as by the angle from which the system is viewed) and whose period is that of the rotating neutron star. Instead, however, we consider a moving target in the form of a clump of matter which has been torn from the accretion disk due to instabilities near the inner magnetosphere.

In Figure 3 we depict a broad particle beam (of width $\Delta\theta$) impinging on target matter which is orbiting a neutron star with a period P_K shorter than the rotational period of the neutron star P_{NS}. Because the particle beam rotates with the neutron star, the target will slowly shift in phase relative to the beam. The γ-ray signal, which may be observed only when the target matter is directly along the line-of-sight to the neutron star, will exist as long as the target remains within the beam and will exhibit the periodicity of the orbiting target rather than that of the neutron star. The duration of such episodic emission is ideally determined by the angular width of the beam and the difference in period of the orbiting matter and the rotating beam (assuming that the clump of material remains stable for a large number of rotations about the neutron star):

$$\tau = \frac{\Delta\theta}{2\pi}\left(\frac{1}{P_K} - \frac{1}{P_{NS}}\right)^{-1} .$$

In reality, however, the target matter will become trapped onto magnetic field lines and forced into corotation, eventually accreting onto the magnetic poles. Thus, the angular velocity of the matter must be expected to change as the process of accretion onto the neutron star evolves (which will result in an increase in the duration of the episode of emission). For this reason, the γ-ray period may be expected to contain a $\dot{P}$ term due to the change from Keplerian to corotation period. If this term is neglected in the search for periodicity, the apparent light curve of the emission may be broadened by the slowly changing period.

IV. SIZE OF TARGET REGIONS

Given the quantities summarized in Table 1, we may estimate the size of the target regions required for conversion of energetic charged particles to γ-rays. In order for the target to act as an efficient production site, the total path length represented must be sufficiently large to ensure the production of the γ-rays while not being so large as to attenuate the signal. To obtain an order of magnitude estimate of the size of such a target, consider a clump of material of thickness $0.1\lambda_p$, where λ_p is the interaction length for *p*-*p* collisions, which has been torn from the accretion disk in the vicinity of r_{cor}. At TeV energies, $\lambda_p \sim 40$ g cm^{-2}. A proton beam impinging on such a target will produce, on the average, 10 γ-rays per proton interaction, each with $\sim 1/30$ the energy of the primary proton. The inter-

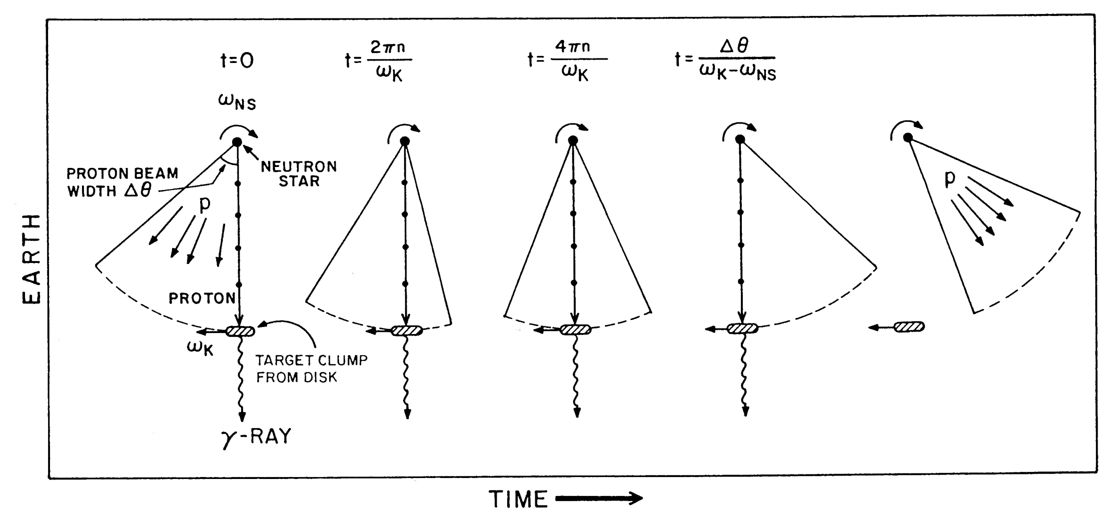

FIG. 3.—Schematic diagram depcicting the interaction of a broad particle beam with target matter orbiting neutron star with a period smaller than the rotational period of the star (and particle beam). As time progresses, the target advances with respect to the beam.

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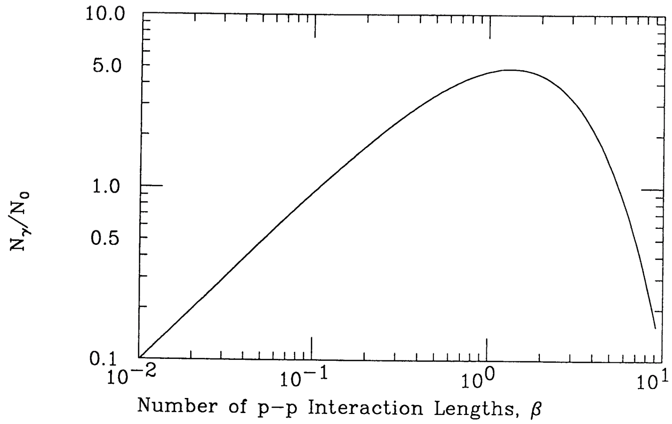

FIG. 4.—Proton to γ-ray conversion ratio. Here β represents the number of *p-p* interaction lengths traversed. We assume an average of 10 γ-rays result from each proton interaction (each with $\sim 1/30$ of the primary proton energy).

action length λ_γ for γ-ray absorption at TeV energies is $\lambda_\gamma \sim 75$ g cm^{-2}. For a target thickness of $0.1\lambda_p$, the overall rate for emitted γ-rays is approximately equal to the incident proton rate (see Fig. 4). Since the density of the disk material in the vicinity of $r_{\rm cor}$ is $\rho \approx 1.4 \times 10^{-4}$ g cm^{-3}, the thickness of the target is $\sim 2.8 \times 10^4$ cm. This is considerably smaller than the disk thickness at $r_{\rm cor}$.

Given the size of such a target region, some characteristics of the associated γ-ray light curve may be inferred. Assuming that the material orbits Her X-1 at a distance $r_{\rm K} \approx r_{\rm cor} \approx 10^8$ cm, the duty fraction of the light curve (i.e., the fraction of the light curve over which the γ-rays are produced) is

$$\delta \approx \frac{10^4}{10^8} = 10^{-4}$$

assuming a spherical shape. Such a sharp light curve is in conflict with those observed. However, because the matter which is removed from the disk quickly changes its orbital velocity, the resulting target distribution may well be more in the form of a stream of material which would yield a broader light curve. Further, as noted above, considerable broadening of a sharp light curve may occur if the transition from Keplerian orbit to corotation is sufficiently rapid. To see this, consider the calculation of the phases associated with given event times:

$$\phi(t) = \phi_0 + \frac{t - t_0}{P_0} - \frac{1}{2}\left(\frac{t - t_0}{P_0}\right)^2 \dot{P} .$$

Taking $t_0 = 0$ and $\phi_0 = 0$, we have

$$\phi(t) = \frac{t}{P_0} - \frac{1}{2}\left(\frac{t}{P_0}\right)^2 \dot{P} = n$$

for very sharp light curves (i.e., we consider each event to fall at multiples of $\phi = 1$). The event times for such a light curve are then given by

$$t_n = \frac{P_0}{\dot{P}}\left(n\dot{P} + \frac{n^2\dot{P}^2}{2}\right) .$$

If $\dot{P}$ is neglected in calculating phases for such event times, the error in phase is

$$\Delta\phi = \frac{n^2\dot{P}}{2} .$$

Given a light curve with duty cycle $\delta \sim 0.5$ and $n \sim 10^3$ (Resvanis *et al.* 1988) we have $\dot{P} \sim 10^{-6}$. Thus, while a broad light curve can easily be accommodated given the above scenario, a limit on $\dot{P}$ can be established on the basis of detection of the signal without the inclusion of a $\dot{P}$ term.

As mentioned above, a broad light curve may also result from the actual spreading of the target. Differential rotation effects, for example, would tend to produce an azimuthal spread in the matter distribution (although some local stabilizing effects may act to resist such spreading). In order to maintain the overall rate of accretion onto the neutron star, the rate at which turbulent clumps are removed from the disk must be high. If the majority of the matter becomes spread out into a somewhat uniform flow by the time it has approached the line of sight, then a thin target for producing γ-rays at the rotation period of the neutron star may exist. However, the reduced path length represented by this matter would result in a significant reduction in the γ-ray signal. Hence, it is possible that VHE bursts are only observed when a clump from the disk remains stable long enough to cross the line of sight to provide a more efficient target.

V. DISCUSSION

We have suggested that a measured TeV period of 1.23593 s from Her X-1, associated with a burst of duration $\sim 10^3$ s (Resvanis *et al.* 1988) may be associated with bombardment of target matter torn from the accretion disk by a beam of energetic protons. A target orbiting the neutron star only 0.1% closer than the corotation radius (which is known to be a region of instability at the disk surface) could result in such periodicity. The many other anomalous periods shown in Figure 1 may be explained in a similar manner by instability regions at radii either slightly larger, or slightly smaller, than $r_{\rm cor}$.

Because of the low signal-to-noise ratio in VHE γ-ray experiments, the search for periodic emission is generally confined to periods at or around the neutron star rotation period. Given the model outlined above, however, it is clear that periods near, but distinctly different from that of the neutron star are possible. In light of this fact, it seems worthwhile to investigate existing data for such effects. We note that many of the "beat-frequency" models for QPO behavior (Alpar and Shaham 1985; Lamb *et al.* 1985; Morfill and Trümper 1986) which are currently popular are based on accretion disk matter in Keplerian orbits in the vicinity of the outer magnetosphere of a central compact object. In these models, the frequency of the observed emission is some multiple of the frequency of the beats between the neutron star rotation period and the Keplerian period of the disk matter. If the additional constraint that the disk matter must lie between the observer and the neutron star is added (as shown in Fig. 3) then resultant periods cannot be shorter than that of the neutron star rotation period. Thus the model proposed here for anomalous VHE γ-ray periodicity cannot accommodate a beat-frequency scenario (in that some of the measured periods are indeed shorter than that of the neutron star). This does not suggest that such a picture cannot be realized for QPO behavior, however, in that the additional constraint is not required for the corresponding QPO signal. Indeed, evidence for the existence of clumps of material near the accretion disk/magnetosphere interface is supportive of such models. As such, continued investigation of QPO behavior from such objects as

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Her X-1 could serve to establish links to VHE results. We note that the effective path lengths presented by the proposed accretion disk clumps are considerably longer than the mean free path for X-ray absorption ($\lambda_X \approx 2.5$ g cm^{-2} given the Thomson cross section $\sigma_T \approx 7 \times 10^{-25}$ cm^2). Thus, we may expect such clumps of matter to act as efficient absorbers of X-rays. Analysis of existing X-ray data from Her X-1 and similar objects to search for the effects of the resulting "anomalous absorption dips" is thus warranted. Further, coordinated simultaneous observations of such objects in VHE γ-rays, X-rays, and optical bands should be carried out in an effort to investigate the possible correlation between QPO behavior and anomalous periodicity at VHE energies.

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