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TeV AND PeV GAMMA-RAY EMISSION FROM ACCRETING PULSARS

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ABSTRACT

We discuss a corotating jet model for the high-energy γ-ray emission of accreting pulsars, which explains the pulse, orbital, and longer time scale behavior reported in the TeV and PeV ranges for Her X-1, 4U 0115+63, Vela X-1, and LMC X-4. This model is compatible with our present observational and theoretical understanding of the X-ray properties of these objects, and is based on the fact that the accreting pulsars confirmed so far as high-energy sources appear to have a nearly corotating magnetosphere.

Subject headings: gamma rays: bursts — pulsars — radiation mechanisms — stars: accretion — X-rays: binaries

I. INTRODUCTION

Gamma-ray emission above TeV (10^{12} eV) and PeV (10^{15} eV) energies has been reported for at least four accreting X-ray pulsars, namely, Her X-1, 4U 0115+63, Vela X-1, and LMC X-4 (see Hillas 1987 for a recent review). The inferred time-averaged fluxes are comparable to the X-ray fluxes, in the range 10^{36}–10^{38} ergs s^{-1}, and the identification with these objects has been aided by the fact that a significant fraction of this high-energy emission is pulsed with characteristics essentially similar to those of the X-ray emission. There are also reported observations at TeV energies for several rotation-powered (radio) pulsars, including the Crab and Vela pulsars, PSR 1937+21 (the 1.6 ms pulsar), and PSR 1953+29 (the 6 ms binary pulsar). The range of luminosities for this second class of objects is lower, $\sim 10^{34}$–10^{35} ergs s^{-1}, and so far the emission seems to have been confirmed only at TeV, not at PeV, energies. There are thus at least two distinct types of pulsars which are believed to emit above 10^{12} eV, as well as at lower energies. Another notorious object, Cyg X-3, which is one of the most observed at TeV and PeV energies, cannot yet be clearly classed into one of the two categories above, and either may be a transitional case or may represent a class in itself. As pointed out by various authors (e.g., Orford 1987), the TeV emission of rotation-powered pulsars at the levels observed may be understood in terms of spark-gap or similar models, and here we shall not discuss these objects. In the present paper, we restrict our attention to the class of those bona fide accreting binary pulsars which have been observed to radiate in the TeV and/or PeV range. The advantage (e.g., Weekes 1986) is that for these a wealth of dynamical information exists; but, even so, the uncertainties are enough to allow only a tentative model.

The need for a better theoretical understanding of the ultra–high-energy radiation in accreting pulsars increases in proportion with the declining skepticism about the reality of some of the observations in this range. While the interpretation of the observed high-energy events as photons is not yet entirely secure at PeV energies, the atmospheric Cherenkov observations at TeV energies are widely accepted as such, and here we shall assume that both the TeV and PeV events detected are photons. For the three Galactic accreting pulsar sources, each of the γ-ray observations has been confirmed by at least one other independent group, either in the same energy band or in a different one. Only for the extragalactic source LMC X-4, which requires longer observing times, is a confirming observation still missing. On the other hand, there is a wealth of data at X-ray energies in accreting pulsars, involving spin, orbital, and sometimes longer periodicities, and there are fairly good determinations of the masses, the type of companion, some magnetic field strengths, and various parameters of the accretion geometry. Thus one faces the challenge to find a general model of the high-energy emission, which at the same time is in consonance with current models of the X-ray emission of accreting pulsars. The latter area is phenomenologically and theoretically rather developed, to the point that one can speak of generic X-ray emission models, applicable to all sources in one form or another. The TeV–PeV radiation, on the other hand, has been interpreted mainly on a source-by-source basis, many of the models having been tailored to the peculiar source Cyg X-3. There are currently three main types of high-energy generation mechanisms worked out in some detail, all three based on particle acceleration up to about 10^{16} eV in the neighborhood of the neutron star. These are the accretion shock acceleration models (e.g., Eichler and Vestrand 1984; Kazanas and Ellison 1986), the neutron star–disk unipolar inductor model (Chanmugam and Brecher 1985), and the jet acceleration model (e.g., Quenby and Lieu 1987). So far there have been only modest attempts at checking whether the proposed high-energy mechanisms can coexist with the accepted X-ray emission mechanisms. Our main concern in this paper is to develop a simple model which is compatible with the various observations in both of these energy ranges. For this reason, we present a rather detailed discussion of the observations and of the uncertainties involved, as well as of the physical assumptions made in developing models.

In the present paper we briefly summarize in § II the high-energy and X-ray observations of accreting pulsars, and we seek to establish the features that are general to all cases. In § III we develop a general model of the high-energy emission, which applies to all currently identified accreting pulsars active in this range, and which is in agreement with the observations and current models of the X-ray emission. In § IV we discuss the specific observations of Her X-1, 4U 0115+63, Vela X-1, and LMC X-4 and compare these with the results from this

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model. In § V we compare with previous work and discuss some of the theoretical observational aspects of this model.

II. OBSERVATIONAL OVERVIEW AND A POSSIBLE MODEL

The predominant method of observation at TeV energies is the detection of Cherenkov light originating from small air showers high in the atmosphere, while at PeV energies the charged-particle content of air showers is directly observed either near sea level or at mountain altitudes. The first type of observations is restricted to moonless clear nights, while the second type provides a continuous drift scan over practically continuous periods of several years. While the first type is better suited to detecting bursts of several minutes to hours, the second type is more suitable for steadier sources with longer periods. The most constraining features about the high-energy γ-ray emission of the accreting pulsars considered are that the inferred particle luminosities are comparable to the X-ray luminosities and that in three out of four cases (Her X-1, 4U 0115+63, Vela X-1) some of the high-energy emission is pulsed at the pulsar period. All four of them also show modulation with the orbital period, and the emission is stronger at some orbital phases. In at least one source which shows long-term periods with X-ray ON and OFF periods (Her X-1), the γ-rays are not seen during most of the X-ray OFF periods. Two of the sources have been observed at both TeV and PeV energies (Her X-1 and Vela X-1), while so far 4U 0115+63 has been reported only at TeV and LMC X-4 only at PeV energies.

On the other hand, a common feature of the X-ray emission of all four observed γ-ray–emitting accreting pulsars is that they seem to be sources which are near corotation (Lamb and Weekes 1986; Trümper 1987). They alternate between periods of spin-up and spin-down; the value of $\dot{P}/P$ is rather low compared with that in most accreting pulsars (see Joss and Rappaport 1984), and the interpretation is that the magnetospheric (Alfvén) radius is close to the corotation radius (see Ghosh and Lamb 1979). In at least two of them (Her X-1 [see Trümper 1987] and Vela X-1 [see Börner *et al.* 1987]) one infers that the magnetic pole passes close to the line of sight. The orbital inclination angle i is large for at least three of them (Her X-1, Vela X-1, and LMC X-4), since eclipses by the companion are seen (see Joss and Rappaport 1984), so that the disk, if there is one, should not be far from edge-on. In at least two of them, additional periodic occultations by a disk or the accretion flow is inferred, from the existence of long term periodicities (Her X-1, 35 days; LMC X-4, 30.5 days).

The observations mentioned, while not unequivocal, are fairly suggestive. Both the X-ray emission and the inferred particle luminosities (which must exceed the γ-ray luminosities by at least 1 order of magnitude) are estimated to be near the Eddington value, which implies that the gravitational potential tapped must correspond to matter penetration distances close to the neutron star surface. Both the X-ray and the high-energy emission (the latter at least some of the time) are pulsed, so that strong magnetic field effects may be involved in both. Finally, most X-ray emission models assume this radiation to arise close to the neutron star, but the high-energy γ-rays must originate far enough from the surface, in order not to be downgraded by one-photon pair creation in the pulsar magnetic field. The possibility of a wind model has been suggested (Eichler 1986) to accommodate some of these requirements.

These constraints may be incorporated into the following model. Matter accreted from the companion is channeled toward the polar caps, and some of it reaches the surface, producing X-rays in the usual manner. A significant fraction, however, is ejected along the magnetic axis by radiation pressure near the base of the accretion column, giving rise to a semirelativistic neutral jet, including protons. This jet undergoes a shock transition at a radius close to the Alfvén radius, where there is external material. Protons are accelerated in this shock by scattering off magnetic irregularities in the flow. The dipole field is considerably reduced at this distance, so that the proton radiative losses are reduced and proton energies of order 10^{16} eV can be reached before these escape. The density of the downstream shell material, being near corotation, does not move appreciably sideways with respect to that in the jet, so that a sufficient number of scatterings occur in a coherent beam. A fraction of the proton energy is converted to γ-rays in the shock itself by nuclear interactions, and both the γ-rays and the escaping protons remain beamed along the magnetic axis. The magnetic field is sufficiently weak there that a large fraction of these γ-rays can escape without being destroyed by one-photon pair production, namely, that fraction which is close enough to the magnetic field line directions, which further contributes to collimation of the photon beam. The rest of the photons escape and undergo further nuclear interactions leading to γ-rays when traversing an appropriate amount of accretion disk, wake, or wind material or when traversing the photosphere of the companion star. We enter into some details below.

III. PROPERTIES OF THE COROTATING JET MODEL

a) Conditions at the Magnetospheric Radius

In accreting pulsars, the incoming accreting material is stopped at the Alfvén or magnetospheric radius, where the accreting matter stresses equal the magnetic stresses of the neutron star magnetic field. The magnetospheric radius for spherical accretion is (Lamb, Pethick, and Pines 1973)

$$r_{m,s} \approx 1.5 \times 10^8 B_{*12}^{4/7} R_6^{10/7} m^{1/7} L_{38}^{-27} , \quad (1)$$

where B_{*12} is the magnetic field at the surface in units of 10^{12} G; R_6 is stellar radius normalized to 10^6 cm; and m is mass in solar units. Usually L_{38} is the X-ray luminosity normalized to 10^{38} ergs s^{-1} (the Eddington value is $L_{Ed} = 1.26 \times 10^{38}$ m ergs s^{-1}). Here, however, it represents the total luminosity, including X- and γ-rays and particles, since it is the total mass accretion rate which enters equations such as (1). This expression is also a rough approximation for disk cases, but more specifically we can use for disks the criterion $\rho v_r v_\phi \approx B^2/4\pi$ (see Lamb and Pethick 1974). We apply this to an "alpha disk" model (see regime b of Shakura and Sunyaev 1973) to obtain a disk magnetospheric radius

$$r_{m,d} \approx 10^8 B_{*12}^{40/61} R_6^{104/61} m^{-25/61} L_{38}^{-16/61} \alpha^{-2/61} , \quad (2)$$

where $\alpha \leq 1$ is the disk viscosity parameter, which because of the exponent can practically be ignored. The corotation radius, at which the magnetospheric solid-body rotation implies a tangential velocity comparable to the Kepler (or free-fall) velocity is $r_{co} = (GM/\Omega^2)^{1/3}$, given by

$$r_{co} = 1.5 \times 10^8 m^{1/3} P^{2/3} , \quad (3)$$

where $\Omega = 2\pi/P$ and P is the spin period. The condition of a corotating magnetosphere, which the four accreting pulsars seem to satisfy, is given by setting the Alfvén radius $r_A = \delta r_{co}$, where r_A is either $r_{m,s}$ or $r_{m,d}$ and where $\delta \approx 1$. Using the spherical expression (1), and setting $r_A = \delta r_{co}$, the surface magnetic field in units of 10^{12} G under the assumption of near-corotation is

$$(B_{*12})_{\mathrm{co},s} = L_{38}^{1/2} P^{7/6} R_6^{-5/2} m^{1/3} \delta^{7/4} , \quad (4)$$

where the subscripts co, s refers to the corotating and spherical assumptions. In disk sources, with $r_A = \delta r_{\mathrm{co}}$ and using equation (2), the vaue is only slightly different,

$$(B_{*12})_{\mathrm{co},d} = 1.83 L_{38}^{2/5} P^{61/60} R_6^{-13/5} m^{17/15} \alpha^{1/20} \delta^{61/40} , \quad (5)$$

where the subscripts, co, d refer to the corotating disk assumption. In both equation (4) and equation (5), L_{38} refers to the total accretion energy, including particles. The material in the transition region just outside the magnetosphere, under these conditions, will be rotating at approximately the same tangential speed as the magnetosphere. For spherically accreting sources, the matter may penetrate somewhat lower before acquiring by friction the tangential speed of the magnetosphere. The material at $r > r_A$ is shielded from the neutron star field in the radial case (see Arons and Lea 1980) even above the polar caps. In the disk case, for conditions near corotation one would expect the rotating shell of material displaced from the disk, carrying its own turbulent tangled fields, to act also as a shield for the stellar field. Even in the absence of such a shell, shielding in the disk case is expected to occur at radii $r \leq$ 10–100r_A (see Ghosh and Lamb 1979).

b) Accretion Channel, X-Ray Production, and Jet Formation

Below the Alfvén surface, one expects matter to latch onto the stellar magnetic field lines, thereafter falling along these toward the polar caps. In the nondisk cases the matter may approach the neutron star along a less defined routine than in the disk cases (see Elsner and Lamb 1984). However, one can expect here too that more matter is funneled toward the polar caps, with other secondary avenues distributed perhaps over a broader range of angles. At the high accretion rates envisioned, the matter falling along the field lines is expected to undergo a radiative shock transition. Depending on the details of the Alfvén transition region and the relative inclination between the orbital, spin, and magnetic axes, one may expect (at least in a time-averaged picture) either a filled accretion column, a hollow funnel, or a section of a hollow funnel, with the radiative shock somewhere above the surface (Basko and Sunyaev 1976). The shocked material below the radiative shock is expected to give rise to the X-ray emission. The X-ray emission, based on an analysis of cyclotron line shifts (Mészáros and Nagel 1985*a*, *b*) and/or pulse shapes (Kanno 1980; Nagel 1981) is expected to be pencil-beamed, along the magnetic axis. This pencil beam also can arise for radiation emitted sideways by the column wall, as a result of gravitational bending in compact neutron stars (Mészáros and Riffert 1988). The flow below the radiative shock may become unstable near the surface, since the radiation pressure inside the funnel wall may exceed the magnetic dipole field pressure, for surface fields $\leq 10^{13}$ G. This is certainly the case for Her X-1 and 4U 0115+63, where cyclotron line measurements allow the field to be determined. These instabilities would be expected to lead to X-ray variability (see Basko and Sunyaev 1976). They would also, however, lead to injection of matter into emptier regions where the radiation pressure is high, such as in the funnel interior, followed by the radiative ejection of the matter along the magnetic axis (see Fig. 1). Even for larger fields, the accretion flow is expected to be time-dependent and inhomogeneous at the envisaged accretion rates, and may contain both regions where shocked matter settles downward and regions where matter escaped upward, in the form of radiation-dominated bubbles (see Klein, Arons, and Lea 1985). This would give rise to a radiatively driven axisymmetric wind, whose terminal velocity is expected to be of the order of the escape velocity at the surface, i.e., a fraction of the speed of light. The gravitational energy thus liberated and converted into bulk flow velocity is of the order of magnitude required, for accretion rates which are close to or exceeding the (local) critical rate, $L_c \approx (0.4\text{–}1) \times 10^{37}$ ergs s^{-1} (see Basko and Sunyaev 1976). For lower accretion rates this activity becomes less important or entirely subsides, owing to the lack of radiation pressure.

c) Collisionless Shock in the Jet and Proton Acceleration

The material injected at the base of the jet reaches r_A in a time $t_{\mathrm{jet}} \approx (R_A/0.3c) \approx 10^{-2}$ s, much less than the typical spin period of accreting pulsars. The ejected wind rotates with the neutron star, the matter being quasi-relativistic and following the dipole field lines. Near r_A the protons far from the magnetic axis veer away and head toward the magnetic or angular momentum equator, where they encounter the stream from the opposite pole or the matter from the accretion disk, and they eventually rejoin the accretion flow, being recycled inward again. The wind protons which were ejected close to the magnetic axis, moving quasi-radially, are able to cross over into the region beyond the magnetosphere. A collisionless shock is expected to arise at or slightly before this crossing, supported by the pressure of the external material or fields associated with the Alfvén shell. The presence of this material above the poles and outside the magnetosphere is to be expected in significant amounts in disk sources with an oblique rotator sweeping close to the disk, as suggested in Her X-1 and LMC X-4, and also in wind sources where the infall is quasi-spherical. The protons that undergo this shock form a narrower quasi-radial bundle around the magnetic axis, and this portion of the flow is now better described as a jet than as a wind. The shock will occur at $r \approx r_A$, beyond which material from the disk or the wind has acquired a tangential velocity comparable to that of the magnetosphere, and forms a corotating shell (see Fig. 2). Observationally, this shell is estimated to have a column density of order ~ 1 g cm^{-2} in Her X-1

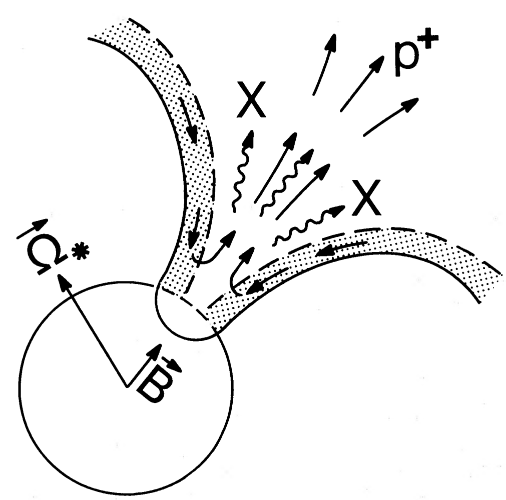

FIG. 1.—Schematic representation of the accretion column showing the incoming accretion flow, the X-ray radiation, and the ejected proton wind.

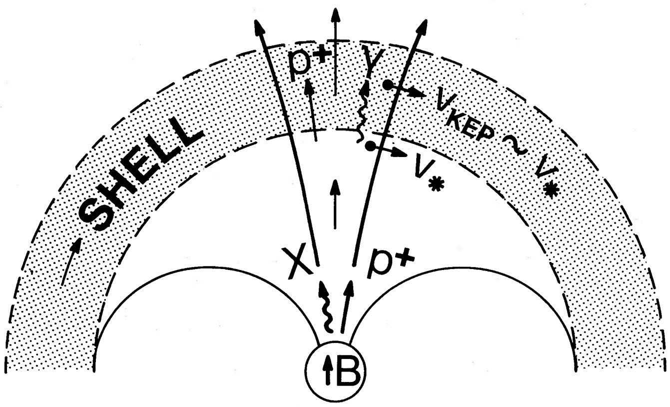

FIG. 2.—The accretion shell (*shaded*) and the shock acceleration region (*dashed lines*), showing the proton and γ-ray jet as well as the X-rays. The magnetosphere, rotating at v_*, is assumed to be nearly corotating with the shell, which moves at $v \approx v_{\rm Kepler} \approx v_*$.

(Kahabka 1987; McCray and Lamb 1976), based on phenomenological arguments for explaining the $E < 1$ keV soft X-rays and the Fe lines observed. In Vela X-1 (Sato *et al.* 1986) and the other two accreting pulsars, similar values are reasonable. Some of the pressure for stabilizing a jet shock is provided by this material, while another fraction may be provided by the entrained turbulent magnetic field in the shell. A significant fraction of the back pressure may ultimately be provided by the accretion flow (disk or spherical) beyond the Alfvén radius. Because of the approximate corotation, the jet will "see" the same material ahead of it for a large number of spin rotations. That is, there is no sideways streaming of the protons being scattered, only scattering up and down the beam. This is important, because the beam must be coherent upstream and downstream over the number of scatterings needed to reach high energies; otherwise the protons might leave the acceleration region prematurely. Proton acceleration can occur in such a shock (Krimsky 1977; Axford, Leer, and Skadron 1977; Bell 1978; Blandford and Ostriker 1978), with downstream protons scattered back by field fluctuations, and upstream protons scattered back by Alfvén waves induced by cosmic-ray streaming. If the field in the downstream region has a tangential component due to shear, the protons suffer there a cross-field diffusion, the effective cycle time being dominated by the slowest of the downstream and upstream backscattering times. Since the cross-field diffusion is expected to have a shorter time scale, the acceleration time is approximately the same as if the downstream field were longitudinal, but the shock stability may be enhanced.

The requirements for shocks to accelerate protons up to PeV energies have been discussed by Kazanas and Ellison (1986) and Eichler and Vestrand (1984). The difference with our situation is that both of these papers assume an acceretion rather than a jet shock (see, also, however, Quenby and Lieu 1987), while Kazanas and Ellison invoke neutrons as the final escaping particles. The maximum Lorentz factor of the protons before escaping the acceleration region can be estimated by stipulating that the acceleration time be shorter than the synchrotron loss time, combined with the requirement that the diffusion length be less than the region size (see Eichler and Vestrand 1984), which can be written in our situation as

$$\gamma_m < \beta\left[\frac{1}{2\xi}\left(\frac{m_p}{m_e}\right)\frac{R}{Z^2 r_e}\right]^{1/3}$$
$$= 8 \times 10^7 P^{2/9} m^{1/9} \delta^{1/3} Z^{-2/3} \beta \xi^{-1/3}\,, \quad (6)$$

where $\beta = v_{\rm shock}/c$, ξ is the scattering mean free path normalized to the proton gyroradius, m_p, m_e are the proton and electron masses, R is the shock radius, Z is the electric charge per unit atomic weight, and r_e is the classical electron radius. The second line of equation (6) follows by taking $R \approx r_{\rm A} \approx \delta r_{\rm co}$ in our model. The acceleration time is

$$t_a = \frac{\xi}{\beta^2 c}\frac{\gamma m_p c^2}{ZeB}$$
$$= 2.7 \times 10^{-2} B_{*12}^{-1} P^{20/9} R_6^{-3} m^{10/9} \delta^{10/3} \xi^{2/3} \beta^{-1} Z^{-4/3}\,, \quad (7)$$

where, for the second equality, in the corotation assumption we have used for γ the value given by equation (6), and for the magnetic field B we use the value at the Alfvén radius, $B_{\rm A} = B_* R_*^3 \delta^{-3} r_{\rm co}^{-3}$. Using for B_* the corotation value given by equation (4) or equation (5), we have an acceleration time in the corotating spherical case

$$(t_a)_{{\rm co},\,s} = 2.7 \times 10^{-2} L_{38}^{-1/2} P^{19/18} R_6^{-1/2} \times m^{7/9} \delta^{19/12} \xi^{2/3} \beta^{-1} Z^{-4/3}\,, \quad (8)$$

and in the corotating disk case

$$(t_a)_{{\rm co},\,d} = 1.5 \times 10^{-2} L_{38}^{-2/5} P^{6/5} R_6^{-2/5} \times m^{-1/45} \delta^{9/5} \xi^{2/3} \beta^{-1} Z^{-4/3}\,, \quad (9)$$

where we have approximated the exponents of P and δ. Typical values of $\beta \approx 0.3$ and $\xi \approx 10$ will lead to an extra factor $\xi^{2/3}\beta^{-1} \approx 15$ with which one has to multiply equations (8) and (9). Other proton-loss mechanisms, besides synchrotron, are considered next.

d) Gamma-Ray Production in the Jet, Accretion Flow, and Companion

The protons are subject also to photo-pion losses in the X-ray radiation field of the pulsar (Kazanas and Ellison 1986). In our model, we expect this effect to operate on the accelerated beam of protons in the jet near the shock. The time scale there is

$$t_\gamma \approx \frac{m_p/m_\pi}{K\sigma}\frac{4\pi r^2}{\eta L_x}\frac{\epsilon}{1+\tau}$$
$$= 1.7 \times 10^{-1} L_{x38}^{-1} P^{4/3} m^{2/3} \delta^2 \eta^{-1} (1+\tau)^{-1} \epsilon\,, \quad (10)$$

where we took $r \approx r_{\rm A} = \delta r_{\rm co}$, ϵ is the X-ray photon energy in keV, L_{x38} is the X-ray luminosity, τ is the Alfvén region's Thomson scattering optical depth ($\tau \approx 1$), $K\sigma \approx 8 \times 10^{-29}$ cm^{-2} is the approximate cross section times the inelasticity factor of the process, and η is the geometric factor ($\eta \gtrsim 2$–4). This time is of the order of (or slightly but not much shorter than) the acceleration time, for $\tau \approx 1$, $\eta \approx 2$, and periods and luminosities of interest here. We expect, therefore, a fraction of the protons above threshold ($\gamma_t \approx 10^5 \epsilon^{-1}$) to produce γ-rays of energies ranging from about $10^{13}\epsilon^{-1}$ to about $10^{-1}\gamma_m m_p c^2 \approx 10^{15}$–$10^{16}$ eV. The near-equality of these two time scales, however, also allows a significant fraction of protons to escape the region altogether. Notice that both the protons and the γ-rays are beamed, since the jet in which the scatterings occur back and forth is expected to be relatively narrow, being confined to the protons which were initially ejected quasi-axially. The γ-rays produced are subject to one-photon pair creation if the magnetic field in the environment is strong enough. The one-photon opacity is $\kappa \approx 4.35 \times 10^7 \bar{B} \exp[-8/(3E\bar{B})]$ cm^{-1} (see Daugherty and Harding 1983), where E is the photon energy in units of the electron rest mass and $\bar{B} = (B/4.4 \times 10^{13}$ G) sin θ, θ being the angle between the photon and the local magnetic field direction. Using the dipole decay law for the field, we can find an approximate expression for the radius at which the one-photon opacity is unity,

$$r_B \approx 2.8 \times 10^8 R_6 E_{15}^{1/3} (\sin \theta/0.17)^{1/3} B_{*12}^{1/3} \text{ cm} , \qquad (11)$$

where R_6 is the stellar radius in units of 10 km, E_{15} is the photon energy in units of PeV, and B_{*12} is the magnetic field at the neutron star surface in units of 10^{12} G. This expression is normalized to a photon angle of 10° with respect to the field. These escape radii are comparable to the corotation radii of the sources considered here (see § IV). Outside of r_A, of course, equation (11) is an upper limit only, since the magnetic field outside the magnetosphere is less than that of the dipole field used in equation (11).

The escaping protons at $r > r_A$ enter a region which is largely shielded from the neutron star magnetic field, and will follow approximately the original jet beam shape. They move radially, and, just like the water from a rotating hose, they spread out azimuthally in a spiral pattern. For an observer at a fixed azimuth they appear to arrive in a pulsed manner, just as the pulsar radiation does, which is assumed to be pencil-beamed, at least for the direct X-ray component. The large inclination angle can cause the beam periodically to intersect the accretion disk (see Fig. 3), which is expected to have bulges or distortions which come into the line of sight at certain phases, and similarly for the accretion wake in wind sources. Gamma rays are then produced by proton-proton collisions when the incidence is grazing, i.e., the path length is $\sim$50–200 g cm^{-2}. When the proton beam is not fully absorbed in the disk, the possibility exists for a fraction of the protons to reach the companion star, depending on the inclination and phase angles, and the arrival rates and directions may be further influenced by steering in the star's magnetic field (Protheroe 1987; Gorham and Learned 1986). Protons going through the bulk of the star produce neutrinos (e.g., Berezinski, Castagnoli, and Galeotto 1986; Gaisser *et al.* 1986), while those which pass through the less dense limb produce γ-rays extending up to the PeV range. Both the γ-rays and the neutrinos are detected at Earth only if beamed toward the observer. Because of asymmetries introduced by the steering mentioned above, this may possibly (see Protheroe 1987) occur only once per phase, not twice.

IV. COMPARISON WITH OBSERVATIONS

The model above has a number of adjustable parameters, some of which reflect the observational uncertainty of quantities such as the neutron star mass (known usually only to 20%–30% accuracy), or the luminosity, which is dependent on the sometimes poorly known distance and the beaming of the radiation. There are also unavoidable model uncertainties, such as the neutron star radius (dependent on both the mass and the equation of state), the fraction δ of the corotation radius that the magnetosphere fills out, and whether the accretion is of disk or wind type, in addition to uncertainties as to the nature of the magnetosphere's structure itself. One should also note that the Alfvén radii derived in § III and by previous authors depends on the assumption that the field is purely dipole, which may not be true. All of these uncertainties are illustrated by a contrast of the measured surface field value of 4×10^{12} G in Her X-1 (Trümper *et al.* 1978) with the values one calculates from the fairly standard equations (4) and (5). If one takes the standard parameters of Table 1, one obtains from the spherical assumption (4) a surface value of 1.6×10^{12} $R_6^{-5/2} \delta^{7/4}$. The disk value (5) gives $3.73 \times 10^{12} R_6^{-13/5} \delta^{3/2}$, a better agreement. Within the context of simple dipole magnetospheric models, probably one should not expect much better than this, although the formal agreement can be improved if one either reduces R_6 or increases δ. For the sake of simplicity we shall assume here that the same equation of state is valid for all four sources. For Her X-1 we take $m = 1.45$, and for lack of more accurate information the same value will also be used in 4U 0115+63. For the other two sources, Vela X-1 and LMC X-4, we use $m = 1.7$ (see Joss and Rappaport 1984; actually the mean of Vela X-1 is 1.85, but 1.7 is within the error bars). We shall use $R_6 = 1$ in Her X-1 and 4U 0115+63, corresponding to 2.3 Schwarzschild radii (see Mészáros and Riffert 1988, who discuss implications of radii $\lesssim 2$ Schwarzschild radii). The equation of state implied by this value is a fairly soft one, including pionization. For the larger mass sources, $m = 1.7$ in Vela X-1 and LMC X-4, the corresponding value for the same

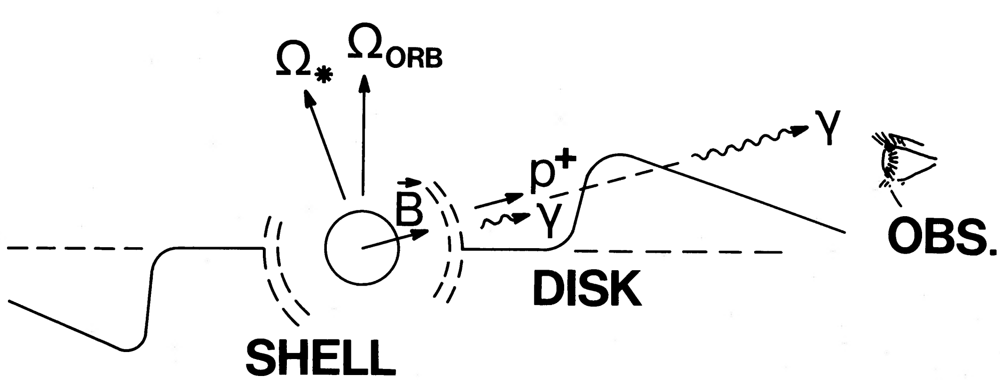

FIG. 3.—A possible configuration for a disk system, showing the orbital angular momentum Ω_{orb}, the spin angular momentum Ω_*, and the magnetic axis B, as well as the shell and the disk. The observer (OBS) is looking along a line close to the magnetic axis when the radiation far from the star is pencil-beamed. The disk is assumed to have warps or bulges which at some values of the orbital (or longer period) phase occult the line of sight. In wind accretion cases, a similar situation may occur with the warp replaced by a wake.

equation of state would be $R_6 = 0.85$. If one thus arbitrarily chooses a radius, the value of δ can be deduced in Her X-1 and 4U 0115+63 by demanding agreement between the theoretical and the observed magnetic field surface value. In Vela X-1 and LMC X-4, δ is undetermined, and we set it equal to unity. One should, however, keep in mind that in all four sources, this set of parameters is far from unique. The models and values used are shown in Table 1. Here L_{38} is total luminosity, including particles ($L_p \approx 10L_\gamma$). Times and periods are in seconds, masses m are in solar masses, radii are in 10^6 cm, and for the two pulsars for which $B_{*12,m}$ (a measured value) exists, the value of δ indicated is that which brings the theoretical field value to equal the observed one; otherwise $\delta = 1$ is used. The labels s and d stand for spherical and disk models. The one-photon escape radius is that calculated for $\theta = 10°$ and the neutron star dipole field at that radius, which as discussed is an upper limit. For the other parameters in equation (8)–(10), we have used as standard values $\beta = 0.3$, $\xi = 10$, $\eta = 2$, and $\tau = 1$. We discuss now the four accreting pulsars individuallly, in terms of the corotating jet model described above, in the light of the current γ-ray and X-ray observations.

a) Her X-1

This source is widely believed to contain an accretion disk, since the companion is of low enough mass that a wind is unlikely and Roche lobe overflow is expected. It also shows evidence for being near corotation, since $\dot{P}/P$ is low and changes sign (see Ghosh and Lamb 1979; Joss and Rappaport 1984). Recent X-ray pulse fits suggest that the magnetic axis sweeps close to the disk plane and to the observer line of sight (Kahabka 1987). It was first detected at TeV energies by the Durham group (Dorthwaite *et al.* 1984) in a 3 minute outburst modulated by the 1.24 s spin period. During the outburst the γ-luminosity was comparable to the X-ray luminosity, and the orbital phase (of period 1.7 days) at which the observation occurred was 0.76. The detection preceded by 35 days a detected X-ray turn-on. This source is characterized by a regular 35 day X-ray cycle, with an 11 day high ON, then OFF, and a secondary low ON in the middle of the OFF period (see Boynton *et al.* 1984), which is interpreted as being due to periodic occultation of the line of sight by bulges in the accretion disk. By using indications for a pulsed flux at other times, a time-averaged γ-luminosity of 2×10^{35} ergs s^{-1} was inferred, which is about 1% of the X-ray luminosity. The light curve seen during the burst contained a broad peak similar to that seen in X-rays. Still in the TeV region and somewhat lower, the Whipple Observatory group made a large number of atmospheric Cherenkov observations of Her X-1 from 1984 to 1986 (Gorham *et al.* 1986*a*, *b*; Gorham *et al.* 1987; Lamb *et al.* 1987*a*, *b*). With three positive detections in 1984, four in 1985 and one in 1986, Her X-1 became the best studied of the four observed accreting pulsars. It is particularly important that one of the 1984 detections was confirmed by the Durham group, looking at the source at the same time (Chadwick *et al.* 1987). The positive results had a nonrandom distribution in the 35 day phase: with only one exception they were all obtained when the X-ray source was supposed to be ON, either high ON or low ON, but simultaneous X-ray detections are not available for most γ-ray detections. Each γ-event was pulsed with 1.24 s spin period. The duration of the events ranged from 25 to 80 minutes, with chance probabilities estimated from 10^{-3} to 7×10^{-6}. The duty cycle for the emission (total time of positive detection per total time of observation) was found to be about 7% for the 1984 and 1985 observations. The 1985 June 16 detection was of particular interest, partly because it occurred at the beginning of an OFF time of the 35 day cycle and also because it occurred during the initial stages of an eclipse by the companion star. The 1.24 s pulsations were clearly seen at a time when the column density of the companion star between the source and the observer was too thick to allow penetration of γ-rays as well as X-rays. This is the clearest indication that at least in some of the events some of the γ-rays are generated in a region different from that which produces the X-rays. It has been suggested that the proton beam giving rise to the γ-rays in the limb of the companion star may have moved on a curved path because of the deflection or steering in the companion's magnetic field (Gorham and Learned 1986). Resvainis *et al.* (1987) also reported evidence for three possible bursts above 300 GeV from Her X-1, using the Haleakala telescope during the low ON phase in the 35 day cycle. So far, there is only one detection above 100 TeV (at about 0.5 PeV), this being a 40 minute burst pulsed with the 1.24 s period detected by the Fly's Eye detector on 1983 July 11 (Baltrusaitis *et al.* 1985). Although at that time Her X-1 had an extended low period in observed X-rays, the optical emission variations caused in the companion by heating from the compact source continued to be seen. Probably the acretion disk was thicker during this time, shielding the observer but not the companion from the X-rays, and also providing material for a proton beam to dump energy generating γ-rays.

In terms of the corotating jet model, the pulsed emission through most of the X-ray ON, and the enhanced emission at some orbital and 35 day phases of Her X-1, arises fairly naturally. We find from equations (9) and (10) (see Table 1) that $t_{a,d} \approx 0.3$, $t_\gamma \approx 0.4$ s for the Her X-1 parameters, using the standard values of β, ξ and the fitted value of δ. For $\delta = 1$ the values are essentially the same, both significantly shorter than a pulse period and than typical burst durations. The value of δ obtained for disks is 1.05, which given the approximations is close enough to unity and implies a surface field equal to the observed 4×10^{12} G. These time scales indicate that the conditions are satisfied for having γ-rays produced in the jet, thus allowing pulsed radiation to be seen beamed in the same way as the X-rays. Using equation (11), based on the stellar dipole field and an angle $\theta = 10°$, one finds that γ-rays up to PeV energies would appear to be able to escape from Her X-1 starting at radii about 4.5×10^8 cm. This is somewhat larger than the corotation radius 2×10^8 cm, although taking θ to be less than about 3° in fact makes the two radii equal. However, as discussed in § II*d*, outside of r_{co} the magnetic field should be that of the shell, expected to be smaller than the dipole field. Some of the one-photon pair creation may occur inside the magnetosphere, and the fact that the two radii can be made equal by decreasing θ may indicate that in Her X-1 the radiation is further collimated by the magnetic opacity, which would cause the radiation beam to be more concentrated toward the magnetic axis. This effect in fact helps in making a well-collimated photon bundle. The similarity of the acceleration and photo-pion time scales is also the condition for having escaping protons at 10^{16} eV, so that when the beam or part of its is not absorbed by the disk, it may reach the star. The probability of this is increased by the X-ray arguments for a magnetic axis close to the orbital plane during significant portions of the 35 day cycle (see Trümper 1987). Thus an addition γ-enhancement is expected from proton interactions occurring at the beginning and end of the X-ray ON periods,

TABLE 1A

OBSERVATIONAL PARAMETERS

Pulsar	L_{38}	L_{x38}	P	m	R_6	$B_{*12,m}$
Her X-1	1.20E+00	2.00E−01	1.24E+00	1.45E+00	1.00E+00	4.00E+00
4U 0115+63	5.00E−02	2.00E−02	3.61E+00	1.45E+00	1.00E+00	1.20E+00
Vela X-1	3.00E−02	3.00E−02	2.83E+02	1.70E+00	8.50E−01	...
LMC X-4	6.00E+00	6.00E+00	1.35E+01	1.70E+00	8.50E−01	...

TABLE 1B

CALCULATED PARAMETERS

Pulsar	Model	t_a	t_γ	δ	γ_m	r_{co}	$r_B(10°)$
Her X-1	s	1.47E+00	1.04E+00	1.69E+00	1.24E+07	1.96E+08	4.43E+08
	d	3.03E−01	3.97E−01	1.05E+00	1.24E+07	1.96E+08	4.43E+08
4U 0115+63	s	1.02E+01	1.61E+01	1.03E+00	1.25E+07	4.00E+08	2.97E+08
	d	1.17E+00	4.34E+00	5.36E−01	1.25E+07	4.00E+08	2.97E+08
Vela X-1	s	1.53E+03	3.75E+03	1.00E+00	4.14E+07	7.72E+09	1.44E+09
	d	8.81E+02	3.75E+03	1.00E+00	4.14E+07	7.72E+09	1.73E+09
LMC X-1	s	4.36E+00	3.24E−01	1.00E+00	2.11E+07	1.01E+09	1.07E+09
	d	2.75E+00	3.24E−01	1.00E+00	2.11E+07	1.01E+09	1.25E+09

when the beam emerges and enters occultation by the disk, and grazes the disk bulges. The grammage needed starts at about 10 g cm^{-2}, but above several hundreds of grams per square centimeter neither protons nor γ-rays are expected to survive. During X-ray OFF periods, when the line of sight crosses the whole disk, neutrinos are expected instead of γ-rays. Actually, this γ-enhancement is observed so far mostly for the beginning of the X-ray ON periods. If confirmed, this may indicate an asymmetry in the disk bulges, such that when the source emerges from behind the disk, the line of sight encounters a more gradual column density drop, and a steeper one when entering disk occultation. The Whipple Observatory detection of TeV radiation just after the end of a small ON and just after the beginning of an eclipse by the companion star may be interpreted (Gorham and Learned 1986) as being caused by proton interactions with the companion's limb, following proton steering in the companion star's magnetic field.

b) 4U 0115+63

This accreting pulsar is an X-ray transient, with a measured magnetic field of $B_* \approx 1.2 \times 10^{12}$ G (White, Swank, and Holt 1983). The low value of the instantaneous $\dot{P}/P$ during accretion episodes, as well as the very low average value over many outbursts (see Kelly *et al.* 1981; Joss and Rappaport 1984), is compatible with the assumption of nearly corotating conditions. The X-ray luminosity is about 2×10^{36} ergs s^{-1} and the period P is 3.61 s (see Rappaport *et al.* 1978; Kelley *et al.* 1981; White, Swank, and Holt 1983). The companion mass is probably above 5 $M_\odot$, and it is not quite clear exactly how the transfer occurs. At high energies, this object has so far been observed in the TeV region only. The Durham group observed it in 1984 as a sporadic source at about 1 TeV, showing the 3.61 s pulsar period (Chadwick *et al.* 1985). The result was confirmed by the 1985 observations of the Haleakala group (Resvainis *et al.* 1987) and by the Whipple Observatory group (Lamb *et al.* 1987*a*, *b*). The light curve of the pulsed radiation is sinusoidal, containing no significant higher harmonics. Taking the distance of the source to be 2.5 kpc, the luminosity was estimated at 2×10^{35} ergs s^{-1} above 0.6 TeV during the October 1985b detection (Lamb *et al.* 1987*a*, *b*). The fluxes observed by the Haleakala group were comparable, while the Durham group found a higher value. No obvious correlation with the 24.3 day orbital phase was found. The fraction of time in which the TeV source is in a high state is fairly small, probably between 1% and 10%. In terms of the corotating jet model, if we use disk accretion, the acceleration and photo-pion time scales are about 1 and 4 s, respectively, with $\delta \approx 0.54$. For spherical accretion they are about 10 and 16 s, respectively, and $\delta \approx 1.03$. The disk values of δ would be closer to unity if the (undetermined) neutron star mass m is less than 1.45 or if $L_{38} \lesssim 0.02$. Also, the photo-pion time may be smaller if L_{x38} is less than 0.02. The above values assume $B_{*12} = 1.2$ (White, Swank, and Holt 1983). If instead the initially reported value of $B_{*12} = 2.5$ is used (Wheaton *et al.* 1979), the disk time scales are $t_a = 3$, $t_\gamma = 10$, and $\delta = 0.87$, with larger values for the spherical case. In any case, the closeness of the time scales allows pulsed γ-ray production in the jet, the magnetic escape radius (11) being 3×10^8 cm for $\theta \lesssim 10°$, which is close to the corotation radius of 4×10^8 cm. The time scales are comparable to the pulsation time, and if corotation is not perfect (since δ should vary with the time-dependent accretion rate), one may expect a decrease in the γ-rays at the highest (PeV) energies. However, the fact that some orbital phases show an excess suggests that accretion flow or stellar surface interactions occur, caused presumably by escaping protons at energies $\sim 10^{16}$ eV (see eq. [6]). Beam coherence in this system ($t_a \gtrsim P$) may start deteriorating at the highest energies, except when $\delta \approx 1$, diminishing first the pulsed fraction and then the flux in the PeV range.

c) Vela X-1

In Vela X-1, whose companion is a massive star, the mass transfer rate occurs via a wind, and the approach to the magnetosphere may be quasi-radial, or possibly via an accretion wake (Nagase *et al.* 1984*a*, *b*), with typical wake hydrogen column densities of 3×10^{23}–10^{24} cm^{-2}. Short episodes of spinning up or down have also been interpreted as possible evidence for a small, temporary disk (Boynton *et al.* 1984;

Börner *et al.* 1987). In either case, the low absolute value of $\dot{P}/P$ and frequent changes of sign seem compatible with our assumption of a corotating shell of material, possibly with $\delta \lesssim 1$. Assuming spherical infall (or using the similar disk formulae), one would estimate a surface magnetic field of $B \approx 2 \times 10^{14}$ G, using $L_{38} = 0.03$, $R_6 = 0.85$, $m = 1.7$, and $\delta = 1$. By taking $R_6 = 1$, $\delta = \frac{1}{2}$ it could be reduced to $B_* \approx 4.4 \times 10^{13}$ G, still large. Such values (similar ones have been inferred by other authors as well; see Börner *et al.* 1987; Kanno 1980) may be unrealistic. This would not be surprising considering the fact that the Vela X-1 system has indications of all three accretion modes (disk, wind, and wake; for the latter two no good torque estimates exist), but at any rate it gives an upper limit for B. At high energies the first detection was in the PeV range (Protheroe, Clay, and Gerhardy 1984). Air showers detected as arriving from within 2° of Vela were binned according to the orbital phase of the X-ray source (8.96 days). Only showers with a large shower age were included, a technique also used by the Kiel group for Cyg X-3, the aim being the reduction of the proton-initiated shower background. When the showers were binned into 10 orbital phase bins, only a marginal signal was seen. However binning into 50 bins produced a single-bin sharp peak at orbital phase 0.63, with an estimated significance level of 99.7%, even after allowing for combinatorial factors. A photon luminosity of 2×10^{34} ergs s^{-1} per decade above 3×10^{15} eV was inferred, taking the distance to be 1.4 kpc. This is about 2 orders of magnitude lower than the X-ray luminosity. A much more recent observation at TeV energies (North *et al.* 1987*a*, *b*) confirmed that Vela X-1 emits γ-rays, although the characteristics of the radiation were totally different from those in the PeV region. A smooth, steady sinusoidal change with the 283 s pulsar spin period was found, during the time 1986 April 5 to May 2, with no obvious changes with orbital period except for an outburst during the initial phases of an eclipse. This outburst was also found to show modulation with the pulsar period in phase with the steady signal. The γ-ray luminosity during the steady signal was inferred to be 2.4×10^{34} ergs s^{-1}, while the increase during the outburst may have been as much as a factor of 8 higher. In terms of the corotating model, for standard parameters (Table 1) and a total luminosity $L_{38} = 0.03$, one finds for disk accretion the values $t_a \approx 8 \times 10^2$ s, $t_\gamma \approx 4 \times 10^3$ s. The latter time may be smaller by a factor of 3 if we take $\eta \approx 4$, $\tau \approx 2$, which would be appropriate for a more collimated X-ray beam in a slightly denser environment as inferred in Vela X-1. Since this is a complicated system, the actual values may be different, but the approximate equality of the two quantities is likely to remain, which allows for TeV and PeV γ-ray emission in the jet and significant proton escape at 10^{16} eV. The γ-ray escape radius is here a factor of 4 smaller than the corotation radius, so that pulsed radiation should be seen from this model. However, since the acceleration time for energies of $\sim 10^{16}$ is a few rotation periods, it would not be surprising if the coherence of the pulse modulation of the highest energies were washed out, unless δ is very close to unity. The PeV γ-rays (Protheroe, Clay, and Gerhardy 1984), which are modulated with the orbital period and appear preferentially at $\phi_{\rm orb} \approx 0.51$–0.64, can be produced in this model by the escaping protons interacting with a temporary disk (the wake is probably not dense enough, from X-ray observations, to allow significant conversion). In addition, one might expect that when δ does approach close to unity (presumably when reversals of the sign of $\dot{P}$ occur), the PeV radiation should also be modulated with the pulse period, an effect which has not yet been observed.

d) LMC X-4

This is another transient source, situated in the Large Magellanic Cloud at a distance of 55 kpc, whose X-ray luminosity is estimated at 6×10^{38} ergs s^{-1}. The mass is $m = 1.7$, and the period is 13.5 s, the companion being an early-type O8 III–V star. There are both eclipses by the companion star and a 30.5 day long periodicity interpreted as in Her X-1 as being due to occultation by a precessing disk. The $\dot{P}/P$ is again low and of changeable sign, indicating near-corotation. In LMC X-4 the observational evidence for γ-ray emission is perhaps the weakest. Emission above 10^{16} eV with a periodicity in close agreement with the orbital period of 1.408 days has been reported. This is based on results of a systematic search for periodic emission from 14 southern hemisphere neutron star binaries with known orbital periods, using the Buckland Park EAS array in Australia (Protheroe and Clay 1985). So far, the observation has not been confirmed by an independent group. The excess was found in the orbital phase bin 0.90–0.95, which corresponds to the initiation of the eclipse of the pulsar by the companion. The time-averaged luminosity was calculated as 10^{38} ergs s^{-1} per decade above 10^{16} eV, comparable to the luminosity of 6×10^{38} ergs s^{-1} in the 2–10 keV band. The lack of confirmation at somewhat lower energies, where most arrays operate, is perhaps not surprising, since the attenuation of γ-rays of 10^{15} eV coming from the LMC (55 kpc away) would be more than an order of magnitude, by pair production on the microwave background radiation. Again using standard parameters and equations (8) or (9) and (10) (see Table 1), we see that $t_a \approx 3$ s and $t_\gamma \approx 0.3$ s. The γ-ray escape radius for $\theta = 10°$ is $(1\text{–}1.2) \times 10^9$ cm, essentially the same as the corotation radius. The two time scales could be brought closer together if one increased β or reduced ξ, some justification for which might be afforded by the very large value of L_{38}, or, alternatively, one might reduce η. As it is, however, one expects some fraction of escaping protons leading to orbitally modulated enhancement. Since LMC X-4 is eclipsed by the companion, the γ-rays will be too, and this may be the orbital modulation detected, or else one may be observing disk-grazing occultations. We also expect modulation at the pulse period, and this has not been detected so far.

V. DISCUSSION

a) Comparison of Previous Models

Many of the high-energy γ-ray models in the literature have been aimed at Cyg X-3, because of the large apparent flux at TeV and PeV energies of this source. The uncertainties about the physical nature of this source (whether rotation- or accretion-powered, what the rotation period is, mass and type of companion, and so on) have allowed a number of models to appear viable, and some of these or variants thereof have also been proposed for some of the accreting pulsars dealt with here. Most previous accreting pulsar high-energy emission models fall into one of the three general classes described below.

One class of models invokes for the acceleration the electric field induced in a rotating, conducting disk in the presence of an external, perpendicular magnetic field (Chanmugam and Brecher 1985). Such models in general are known to raise some unsolved questions, some of which we briefly mention.

Assuming that there is a strong enough external field (originating either from the neutron star or from the companion star) and that this does not penetrate the disk, one needs a nonrotating "acceleration channel," equivalent to the nonrotating commutator brushes of a generator, to connect the inner and outer parts of the disk and exploit the potential difference. It is not clear why such a channel or conductor would not rotate with the system, especially in the four pulsars considered here, which are believed to be near corotation. A channel rotating together with the disk would presumably also be penetrated by the magnetic field, and thus $\boldsymbol{v} \times \boldsymbol{B}$ electric fields would prevent acceleration. On the other hand, if there were relative motion, there would also be enormous stresses upon these nonsolid conductors, which would reduce the acceleration efficiency. Of course, some of these difficulties are common to radio pulsar models, which nonetheless seem to work. However, the most severe problem, which is peculiar to the accreting pulsar systems (see Hillas 1987), is that the large radius of the magnetosphere of the accreting pulsar systems ($r \gtrsim 100 r_*$) prevents exploiting the larger part of the gravitational accretion energy in this scheme, so that the accretion rates invoked would have to be 100 times greater.

A second class of models invokes acceleration of particles in an accretion shock near the surface of an accreting pulsar (Kazanas and Ellison 1986; Eichler and Vestrand 1984). This is energetically much more favorable, because one is able to tap a substantial fraction of the accretion energy. The main cause for concern is the huge dipole magnetic field of the neutron star in the acceleration region if the latter is too near, which would effectively prevent both very high energy protons and γ-rays from leaving the system. If one demands the field to be low enough so that synchrotron losses are small and the Mach number large enough for efficient acceleration, the shock must be at least 10–50 neutron star radii away, and therefore only a smaller fraction of the accretion energy can go into high-energy particles. One might have neutrons as the particles taking out the energy (Kazanas and Ellison 1986), and the neutron beam could also give rise to nuclear interactions in a target of appropriate column density. This would lead to a reduction of the output, and acceleration times should be to some extent fine-tuned to secure a maximum output under such circumstances. It is also not clear how one might produce pulsed γ-rays in the accretion flow itself, visible even when far from grazing the disk or companion star.

A third class of models—and we consider these as the most likely—proposes a jet or mildly relativistic wind near the magnetic pole, which would carry out a substantial part of the accretion energy to regions of weaker magnetic field. Most of the $E > 10^{12}$ eV particles would get their energy in some type of shock in those outer regions. The possibility of such models was mentioned by Eichler and Vestrand (1984), Eichler (1986), and a version recently suggested by Quenby and Lieu (1987) has been discussed in some detail, in connection with Cyg X-3, assuming a very fast pulsar (period 12 ms). The details thus are rather different from the longer period (> 1 s) cases discussed here.

b) *Discussion of the Present Model*

The stability of the collisionless shock is poorly understood in all models, and here too one has to be concerned with whether there is sufficient pressure behind the shock to stabilize the latter. As mentioned in § II, the fact that the stellar magnetosphere ends there, and that the external shell may have tangential magnetic fields, would contribute to making this a natural region for a shock to occur and also perhaps to stabilizing it, but a rigorous justification is lacking. The presence of the accretion disk or the quasi-spherical flow above or close to the magnetic axis adds a substantial natural source of back pressure. On the other hand, if this surface was not entirely stable, this might help to explain some of the flaring type behavior of the γ-ray emission. For the $B_* \lesssim 10^{13}$ G neutron stars, flaring may also be induced by plasma instabilities in the column (see § II). However, the observational time scales are long compared with any instability time scales, so that one lacks the possibility of a direct check. Another concern is the width of the γ-ray and proton beams. Both would presumably be widened by magnetic deflection effects on the protons, especially near the escape ($>$ PeV) energies. However, for sources such as Her X-1 (see our discussion in § IV), one can achieve significant collimation of the PeV γ-rays due to one-photon pair creation in the magnetic field at the Alfvén surface, which tends to allow out only photons rather close to the axial field lines. This mechanism may also partly contribute to the γ-ray beaming of the other three sources.

Among the advantages of the corotating jet model is the fact that it makes efficient use of the accretion energy, since both the X-ray–producing and the jet material is assumed to approach close to the neutron star surface. While details of the flow are not easy to calculate, this is certainly an idea with a long tradition in accretion physics. Also, the flaring behavior arises naturally, by instabilities near the base of the funnel which eject variable amounts of matter, and/or instabilities at the magnetosphere which allow inward variable amounts of matter and angular momentum. The model exploits the observational evidence for a corotating magnetosphere and accretion disk or flow, to explain the coherence of the acceleration process to high energies. The longer term sporadic γ-ray activity can be explained with modest departures from the corotation conditions. When corotation is not present, the ejected protons cannot be accelerated to high energies, and they eventually rejoin the accretion flow, or diffuse out of the system. The model allows formation of the γ-rays far enough from the neutron star to avoid one-photon pair creation, but near enough to explain pulsations in phase with the X-rays, even when well away from ingress or egress from companion or disk occultation. It also explains the beaming of the high-energy protons and photons along the magnetic axis, that being the natural direction in which an escaping flow can undergo a shock and along which the one-photon absorption is lowest. The model predicts that pulsed PeV radiation should be present in LMC X-4, and possibly in 4U 0115+63 and Vela X-1. The optimal time for detecting this is when the sources are closest to corotation, e.g., as evidenced by a change of sign or a very low value of the X-ray $\dot{P}/P$. Other accreting pulsars would be expected to be visible as pulsed high-energy γ-ray sources only if and when they fulfill the nearly corotating condition.

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Note added in proof.—The X-ray pulsar Cen X-3 has recently been reported by the Durham group (Caraminana *et al.* 1988, preprint) to have episodes of pulsed TeV radiation at the X-ray period of 4.8 s, at phase 0.7–0.8 of the 2.1 day orbital period. While Cen X-3 does not have a $\dot{P}/P$ as low as the other sources here, it is nonetheless subject to episodes of spin-down and spin-up superposed on the overall slower secular spin-up. In this respect, its behavior is reminiscent of Vela X-1 (cf. Nagase *et al.* 1984*a*), and we expect the high-energy radiation episodes to be associated with a change in the sign of the period derivative.

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