A MODEL FOR THE UHE GAMMA-RAYS FROM HERCULES X-1

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ABSTRACT

An outburst of gamma-rays with energies $E_\gamma > 10^{12}$ eV was recently detected from the X-ray pulsar Hercules X-1. The outburst had a 3 minute duration and occured at a time during the 35 day X-ray modulation that is associated with X-ray turn-on. The gamma-rays also have the same 1.24 second modulation that is observed at X-ray energies. Subsequently a 40 minute outburst was detected at $E_\gamma > 10^{14}$ eV. We show how the interaction of ultra-high energy particles with a precessing accretion disk can explain the observed gamma-ray "light" curve. We also discuss the constraints one can place on acceleration mechanisms and the possibility that the UHE particles are accelerated by shocks in an accretion flow.

1. The Higher Energy "Light" Curves. Recently an outburst of very high energy (VHE) gamma-rays, $E \simeq 1$ TeV, was detected from the Hercules X-1 system.[1] The 3 minute outburst was modulated with a 1.24 second period. Subsequent monitoring of the system at ultra-high energies (UHE) by the Fly's Eye [2] yielded evidence for a 40 minute outburst of gamma-rays with energies E > 100 TeV. This UHE outburst also exhibited a 1.24 second modulation and a narrow duty cycle, ~10% of the period. In this section we discuss how these outbursts might arise.

Hercules X-1 is considered by many to be the prototypical binary X-ray pulsar. The x-ray flux displays periodic variations with timescales of 1.24 seconds, ~1.7 days and ~35 days.[3] The two shorter periodicities are interpreted as being due to rotation and occultation of an accreting neutron star that is located in a close binary system. The unusual 35 day flux modulation has an X-ray light curve that is composed of an 11-day high intensity state and a 19-day low intensity state that is interrupted midway between the 11-day high states by an intermediate high state (intensity ~40% of main high state) of 5-day duration.[3,4] The favored explanation for this modulation is that it is produced by the varying aspect of an inclined accretion disk that precesses about the X-ray pulsar.[5,6] Nominal parameters for this system are a disk inclination of 30°, a disk thickness of 25°–45°, and a line of sight that is ~3° below the orbital plane.[4] In this picture, the 19-day low state occurs when our view of the pulsar is obscured by the accretion disk and the 11-day high state occurs when our view is unobstructed. The intermediate high-state is believed to occur when our line of sight nearly grazes the disk and is partially obscured by the disk's corona.

An interesting feature of the high energy gamma-ray outbursts is the phase at which they occur during the 35-day X-ray modulation. The VHE outburst occured on 17 April 1983,[1] the nominal time for the onset of the 11-day high intensity state. On the other hand, the UHE outburst occurred at phase ψ_{35}=0.63.[2] This epoch corresponds to the middle of the period when the intermediate high state is normally observed. It is intriguing that both outbursts occur at a time when our line of sight is grazing the accretion disk.

An attractive explanation of these observations is provided by a geometric "beam dump" model, in which the accretion disk serves as the beam dump.[7] It is related to the model we developed for Cygnus X-3.[8] The idea is that UHE particles are accelerated in a corotating region near the pulsar and then stream outward to interact with the surrounding accretion disk. Energetic gamma-rays will then be detectable when the beam of particles crosses our line of sight and interacts with a column thickness of material that is comparable to the particle's radiation length. A larger column thickness would obscure the photons and a smaller thickness would be inefficient as a converter. In the Her X-1 system this condition is best met at the onset and decline of the X-ray high states when our line of sight is grazing the precessing accretion disk. In fact, the VHE outburst did occur at the nominal time for the onset of the 11-day X-ray high state. However, the production of the UHE outburst during a phase normally associated with the center of the secondary X-ray high state would require a thickening of the disk in order to yield sufficient target along our line of sight. The failure of the EXOSAT X-ray satellite to detect X-ray high states, while optical variability attributed to the reprocessing of X-rays continued, led a number of authors[9,10] to independently conclude that the disk was significantly thicker during this period.

2. Acceleration Efficiency. One of the more remarkable aspects of the gamma-ray observations of Her X-1 is the efficiency that it implies for particle acceleration in the system. Taking, as a conservative estimate, the UHE photon energies to be $E=1\times10^{14}$ eV, the reported time averaged UHE photon flux of 3×10^{-12} cm^{-2} s^{-1},[2] and the duty cycle of 0.1, we derive a peak energy flux of 3000 eV/cm^2. Keeping in mind that the conversion efficiency for UHE particles to photons is only about 10%, we estimate that UHE particles ($E>10^{15}$ eV) are produced about 10 times more efficiently than X-rays! This estimate, which assumes isotropic emission, can be tempered somewhat if the gamma-rays are beamed more than the X-rays. A liberal estimate of the beaming factor can be made by assuming that the fattest part of the beam passes through our line of sight. The solid angle of the beam is then $\pi^3\times10^{-2}$, and the beaming factor is $\pi/4 \times 10^{-2}$. We conclude that the UHE particle luminosity is at least 25% or so of the X-ray luminosity.

This sets strong constraints on models of particle acceleration. For example, acceleration scenarios that invoke the rotational energy of the accretion disk[11] encounter the difficulty that for Her X-1 parameters, which include a surface magnetic field of 4×10^{12} gauss, the inner radius of the accretion disk is located at more than 300 stellar radii. It is difficult to see how more than about 1/300 of the total energy budget could be channeled through rotation of the accretion disk. The fact that the UHE and VHE emission has the periodicity of the neutron star's rotation further supports the notion that the energy that goes into the UHE particles is liberated close enough to the neutron star that the infalling material corotates with it.

The high efficiency associated with shock acceleration makes it an attractive possibility for particle acceleration in Her X-1 system. The shock need not occur at the neutron star's surface for the mechanism to put much of the released gravitational energy into UHE particles; all that is needed is that much of the pressure in the post-shock material that settles on the surface be in the form of UHE particles that are trapped in the flow. However, our understanding of shock acceleration enables us to place strong constraints on models that invoke it. This is the subject of the next section.

3. Constraints on Shock Acceleration. The synchrotron loss timescale for a particle with mass M, energy $E_p=\gamma Mc^2$, and charge Ze is given by

$$\tau_{sy}(E_p) = \frac{4\pi Mc}{\gamma\sigma_T B^2}\left(\frac{M}{Z^2 M_e}\right)^2 \qquad (1)$$

where B is the magnetic field strength in the region. The time required to accelerate a relativistic particle to energy E_p by shock acceleration is

$$\tau_a(E_p) = (\xi R_g)/(\beta_s{}^2 c) \qquad (2)$$

where R_g is the gyroradius ($R_g=\gamma Mc^2/(ZeB)$), ξR_g is the mean free path ($\xi\sim1$), and $\beta_s c$ is the shock velocity. The maximum energy E_d to which a particle can be accelerated by a shock, even in the absence of synchrotron losses, is given by:[12]

$$E_d \approx \frac{1}{\pi}\beta_s ZeBR \qquad (3)$$

where R is the radius of the shock, which must be less than the size of the region. This limit comes from the fact that particles with energies greater than E_d can diffuse away from the system within the acceleration timescale. Stipulating that the acceleration must be faster than the synchrotron loss, and combining this limit with equation (3), we find that the maximum energy $\gamma_m Mc^2$ to which a particle can be accelerated within a compact region of size R is given by

$$\gamma_m = \beta_s\left[\left(\frac{3}{2\pi\xi}\right)\frac{RM}{Z^2 r_o m_e}\right]^{1/3} \qquad (4)$$

where r_o is the classical electron radius.

If the shock velocity is taken to be the free fall velocity at a radius R from the neutron star, $V_{ff}=(2GM_*/R)^{1/2}$, then individual particle energies as high as $9\times10^6 Mc^2 R_6^{-1/6}$ are possible, (where $R = R_6 \times 10^{-6}$ cm). This is sufficient to account for the UHE emission from Her X-1.

A final constraint is that the Alfven Mach number of the shock must be high if much of the energy is to go into the highest energy particles. That is

$$\rho_s u_s{}^2 \gg \frac{B^2}{8\pi} \qquad (5)$$

where ρ_s is the preshock fluid density. If ρ_s is fixed by the condition that

$$\rho_s u_s(\pi R^2) = \dot{M} = \frac{L}{(\epsilon c^2)} \qquad (6)$$

where $\dot{M}$ is the accretion rate, and ϵ is the conversion efficiency from accreted mass to luminosity L, this constrains the magnetic field to be less than $\beta_s^{1/2} L_{38}^{1/2} R_6^{-1} 10^8$ gauss, and R to be less than 10^8 cm. The synchrotron loss limit also constrains B to be less than $7x10^{21} \xi\gamma_m^{-2}$ gauss. We see then that the model demands that the magnetic field within the accretion column be much less than the surface field of the neutron star. This is reasonable because the accreting material is a good conductor and is likely to make its way between field lines of the neutron star on its way to the surface. Alternatively, one could invoke a shock at 10 to 50 neutron star radii, where the field strength of the star's magnetosphere ranges from 10^7 to 10^9 gauss.

4. Discussion. We have proposed that the UHE emission reported from Her X-1 is generated by particles that interact with the surrounding accretion disk. The model predicts that high energy gamma-ray outbursts should occur preferentially at the onset and decline of the high-intensity x-ray states. A fraction of the gamma-rays may be generated within the accretion column. The relative contribution of these two targets depends on the γ-γ opacity. Acceleration by an accretion shock can account for the highest observed gamma-ray energies, but not by a wide margin. Detection of photons at 10^{16} eV or higher would rule out accretion-shock acceleration. Detections at $\sim 10^{16}$ eV of other sources are better explained by shocks in relativistic winds where $\beta \simeq 1/4$, $R > 10^8$ cm, yielding $\gamma_m \gtrsim 10^8$.

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References

1. Dowthwaite, J. et al., 1984, Nature, 309, 691.
2. Baltrusaitis, R.M. et al., 1985, preprint.
3. Giacconi, R. et al., 1973, Ap. J., 184, 227.
4. Jones, C. and Forman, W., 1976, Ap. J. (Letters), 209, L131.
5. Petterson, J.A., 1975, Ap. J. (Letters), 201, L61.
6. Petterson, J.A., 1977, Ap. J., 218, 783.
7. Eichler, D. 1978, Nature, 275, 725.
8. Vestrand, W.T. and Eichler, D., 1982, Ap. J., 261, 251.
9. Parmar, A.N. et al., 1985, Nature, 313, 119.
10. Delgado, A.J. et al., 1983, Astron. Ap. (Letters), 127, L15.
11. Chanmugham, G. and Brecher, K. 1985, Nature, 313, 767.
12. Eichler, D. 1981, Ap. J., 244, 711.