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AND NONTHERMAL PAIR PRODUCTION

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GAMMA RAYS FROM CYGNUS X-1: MODELING AND NONTHERMAL PAIR PRODUCTION

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ABSTRACT

The gamma-ray bump observed between 0.5 and 2 MeV in the spectrum of Cygnus X-1 (Ling et al. 1987) can be interpreted as the thermal emissions from a hot ($kT \sim 400$ keV) pair-dominated cloud. We argue that the X-rays and gamma rays are produced in separate emission regions, and calculate the photon-photon pair production rate from X-ray and gamma-ray interactions in the vicinity of Cyg X-1 by employing a simplified geometry for the two emitting regions.

INTRODUCTION

During a period of about two weeks in the fall of 1979, Cygnus X-1 was observed with HEAO-3 to emit roughly equal fractions of its luminosity in 50-400 keV hard X-rays and 400 keV-2 MeV gamma rays (Ling et al. 1987). The X-ray spectrum of Cyg X-1 in this state (called the γ_1 state) was similar in shape to the normal (γ_2) state spectrum, and the total >50 keV luminosity in the γ_1 state differed by less than $\sim 40\%$ from the total >50 keV luminosity of Cyg X-1 when it is in the γ_2 state.

The gamma-ray spectrum of Cyg X-1 in the γ_1 state is very hard, with photon spectral index ~ 0 at 1 MeV. This gamma-ray "bump" is harder than an optically thin thermal bremsstrahlung spectrum and is suggestive of either a Wien peak or a pair annihilation feature. In other work (Liang and Dermer 1988), we showed that this bump can be self-consistently modeled in terms of the emission from a mildly relativistic pair-dominated plasma. We also argued that the X-rays and gamma rays are produced in different emission regions. Here we summarize these arguments, and calculate the rate of pair production expected from the interaction of X-ray and gamma-ray photons. We find that this mechanism produces a maximum nonthermal pair luminosity of $\sim 3 \times 10^{41}$ e^+e^- /sec, which could lead to a narrow observable annihilation line if the produced positrons leave the interaction region, and rapidly slow down and annihilate in a cold surrounding medium.

SPECTRAL MODELING AND EMISSION REGION PARAMETERS

The allowed states of steady relativistic thermal plasmas with no pair escape are governed by a balance between the rates of pair production and annihilation. For a given proton optical depth, two solutions are possible: a low- z ($=n_+/n_p$, the ratio of positron and proton densities), low-compactness state and a high- z , high-compactness state (e.g., Svensson 1984; Zdziarski 1984). Because most of the energy in the gamma-ray bump of Cyg X-1 is emitted at photon energies above several hundred keV, we require plasma temperatures $kT \sim m_e c^2$ to fit the γ_1 spectrum. At these temperatures the $z \ll 1$ solution produces too soft a spectrum, so we focus on the pair-dominated ($z \gg 1$) solutions.

Using the known luminosity L of the gamma-ray bump and estimating kT from spectral fitting, the dimensionless compactness $l \equiv L\sigma_T/Rm_e c^3$, Thomson depth τ_T , n_+ , and radius R of the hot pair cloud are uniquely determined from results of studies (Svensson 1984; Zdziarski 1984) of steady thermal plasmas in pair balance. When $kT = 400$ keV, for example, we find that $l \approx 12$, $\tau_T \approx 2$, $n_+ \approx 6 \times 10^{16} \text{ cm}^{-3}$, and $R \approx 2.5 \times 10^7 \text{ cm}$. The spectra calculated through Monte Carlo techniques (Liang and Dermer 1988) at $350 < kT < 450$ keV provide a good fit to the γ_1 data at photon energies > 400 keV. When the Monte Carlo results are subtracted from the γ_1 data, the residual spectrum closely resembles the shape of the γ_2 spectrum, suggesting that the gamma rays are produced in the inner region of the accretion flow at the expense of the normal power-law hard (< 400 keV) X-rays (cf. Fig. 1 of Liang and Dermer 1988).

We also considered whether the emission regions can share photons or are spatially distinct. We found that if there is significant Compton reprocessing of the hard X-rays by the pair cloud, then we no longer obtain a good fit to the hard X-ray spectrum. Likewise, if the gamma rays are Comptonized by the plasma responsible for producing the hard X-rays, the gamma-ray spectrum is grossly distorted. We therefore suggested that the hard X-rays are produced by an accretion disk ($kT \sim 90$ keV, $\tau_T \sim 1$) which is physically distinct from the quasi-spherical pair cloud responsible for the production of the gamma rays. But we did not consider nonthermal pair production associated with X-ray and gamma-ray interactions outside the region occupied by the disk and thermal pair cloud. Because of the large X-ray luminosity of the X-ray disk, significant distortions of the gamma-ray spectrum from the pair cloud could occur. Moreover, a nonnegligible amount of cool pairs might be produced through photon-photon pair production and contribute to an outflowing pair wind and possibly to an observable line from annihilation of the positrons in the circumstellar medium. In the next section, we calculate the rate of pair production via this mechanism, and the differential angle and energy spectra of the positrons produced in photon-photon interactions outside the pair cloud.

PAIR PRODUCTION FROM X-RAY AND GAMMA-RAY INTERACTIONS

We approximate the X-ray and gamma-ray emitting regions by a ring of radius r and a point source located at the center of the ring, respectively, as shown in Fig. 1. The ring, representing the X-ray emitting accretion disk, is assumed to radiate isotropically at each point and to have a spectrum, when integrated over the circumference of the ring, equal to that of the residual γ_1 spectrum after subtraction of the spectrum of the gamma-ray bump. For the spectrum of the central gamma-ray source, we use the $kT = 350$ and $kT = 450$ keV spectra discussed in the previous section. Note that the results of this calculation give the maximum possible pair production rate from X- and gamma-ray interactions, as it concentrates all of the hard X-ray flux in a region closest to the gamma-ray source, and includes pair production from a region that is actually within the finite volume of the gamma-ray source. The calculation neglects, however, pair production from interactions of gamma-rays with each other outside the pair cloud. This contribution may be particularly significant if the pair cloud is quasi-spherical or toroidal in shape.

Fig. 1. Geometry of X-ray and gamma-ray photon-photon interactions used in calculations.

Let the spectral emissivity of the gamma-ray point source be denoted by $Q_1(\epsilon_1)$ [photons/($\epsilon_1 \cdot s^{-1}$)], where ϵ_1 is the photon energy in units of $m_e c^2$. The density of photons at a distance x_1 from the central point source is given by $n_1(x_1, \epsilon_1) = Q_1(\epsilon_1)/4\pi x_1^2 c$. The spectral emissivity per unit radian from the ring source is given by $dQ_2(\epsilon_2)/d\omega$, and the photon density at a distance x_2 from an element $\delta\omega$ of the ring is given by $n_2(x_2, \epsilon_2) = \delta\omega(4\pi x_2^2 c)^{-1}(dQ_2(\epsilon_2)/d\omega)$. The differential pair production rate from photon-photon interactions in the volume element δV is therefore given by

$$\delta \dot{N}_+ = \delta \epsilon_1 \delta \epsilon_2 \delta V n_1(x_1, \epsilon_1) n_2(x_2, \epsilon_2) c \sigma_{\gamma\gamma}(s)(1 - \cos\theta), \quad (1)$$

where the invariant quantity $s = 1/2 \epsilon_1 \epsilon_2 (1 - \cos\theta)$ ($s > 1$ for pair production to occur; see Gould and Schreder 1967), θ is the angle between the directions of the interacting photons with energies ϵ_1 and ϵ_2 , and $\sigma_{\gamma\gamma}$ is the total photon-photon pair production cross section. In the following derivation, we use the cross section $d^2\sigma_{\gamma\gamma}/d\mu^* d\phi^*$ differential in the direction cosine $\mu^* = \cos^{-1}\theta^*$ and angle ϕ^* of an outgoing positron in the center-of-momentum system of the colliding photons (Jauch and Rohrlich 1976).

Let θ_1 and θ_2 represent the angles between the x axis and the directions of two interacting photons with energies ϵ_1 and ϵ_2 , respectively (Fig. 1). The differential volume element $dV = d\phi d\cos\theta_1 x_1^2 dx_1$, where ϕ is the angle between the x-z plane and the plane defined by the directions of the colliding photons. Taking into account the threshold condition, the total pair production rate is given by

$$\dot{N}_+ = c \int_0^\infty d\epsilon_1 \int_{1/\epsilon_1}^\infty d\epsilon_2 \int_{-q}^1 d\cos\theta_1 \int_0^{x_1^{\max}} dx_1 x_1^2 \int_0^{2\pi} d\phi n_1(\epsilon_1, x_1) \int_0^{2\pi} d\omega \frac{dn_2(\epsilon_2, x_2)}{d\omega} \times (1 - \cos\theta) \int_{-1}^1 d\mu^* \int_0^{2\pi} d\phi^* \frac{d^2 \sigma^*(s; \mu^*, \phi^*)}{d\mu^* d\phi^*}, \quad (2)$$

where $q = (\epsilon_1 \epsilon_2 - 2)/\epsilon_1 \epsilon_2$, $x_1^{\max} = r \cos\theta_1 + r q \sin\theta_1 / \sqrt{1 - q^2}$, and $x_2 = \sqrt{(r^2 + x_1^2 - 2rx_1 \cos\theta_1)}$.

We integrate equation (2) using the Monte Carlo method (see Ramaty and Mészáros 1981; Dermer and Ramaty 1986). Select a set of 8 numbers $r_1, \dots, r_8$ chosen randomly between 0 and 1. Because of the exponential cutoff in the gamma-ray spectrum, we sample ϵ_1 over only a limited energy range by taking $\epsilon_1 = 1 + 9r_1$ (i.e., maximum gamma-ray photon energy ≈ 5 MeV). For the spectrum of the hot pair cloud, we fit the numerical results of Liang and Dermer (1988) at $kT = 350$ and 450 keV. We approximate the X-ray spectrum of Cyg X-1 in the γ_1 state by the expression $dN/dAdtdh\nu = 126 [h\nu \text{ (keV)}]^{-2.75}$ below 511 keV. This expression is analytically invertible. Choosing a random number r_2 , the energy ϵ_2 is determined from the relation $\epsilon_2 = [1 - r_2(1 - \epsilon_1^{-7/4})]^{-4/7}$. The remaining variables are determined through the relations $\omega = 2\pi r_3$, $\cos\theta_1 = -q + (1 + q)r_4$, $x_1 = x_1^{\max} r_5$, $\phi = 2\pi r_6$, $\mu^* = 2r_7 - 1$, and $\phi^* = 2\pi r_8$.

The pair production rate, equation (2), becomes

$$\dot{N}_+ = \frac{(4\pi d^2)^2}{8\pi c} \frac{4f_2}{7N_{\text{tot}}} \sum_{i=1}^{N_{\text{tot}}} 9\phi_1(\epsilon_1) (\epsilon_1^{7/4} - 1) (1 + q) \frac{x_1^{\max} (1 - \cos\theta)}{x_2} \cdot 2 \cdot \frac{d\sigma^*}{d\mu^*}, \quad (3)$$

where d is the distance to Cygnus X-1, $\phi_1(\epsilon_1)$ is the fit to the gamma-ray flux of the hot pair cloud as observed at Earth, N_{tot} is the total number of Monte Carlo trials, $f_2 = 126 \times 511^{-1.75}$, and $\cos\theta = (x_1 - r \cos\theta_1)/x_2$. The differential energy and angle spectrum of the produced positrons can be determined from a 4-fold transformation (3 rotations + boost) from the laboratory system reference frame (shown in Fig. 1) to the center-of-momentum system of the colliding photons. In this exercise, we adopted the conventions of Dermer

(1985). The transformation equations for the 4-vector $\pi = (p_x, p_y, p_z, E)$ of the produced positron are

$$\begin{cases} p_x = \bar{p}_x \cos\omega - \bar{p}_z \sin\omega \\ p_y = \bar{p}_y \cos\phi - (\bar{p}_x \sin\omega + \bar{p}_z \cos\omega) \sin\phi \\ p_z = \bar{p}_y \sin\phi + (\bar{p}_x \sin\omega + \bar{p}_z \cos\omega) \cos\phi \\ E = \bar{E} \end{cases} \quad (4a)$$

where

$$\begin{cases} \bar{p}_x = \gamma_c [(p_x \cos\omega - p_z \sin\omega) + \beta_c E] \\ \bar{p}_y = p_y \\ \bar{p}_z = p_x \sin\omega + p_z \cos\omega \\ \bar{E} = \gamma_c [E + \beta_c (p_x \cos\omega - p_z \sin\omega)] \end{cases} \quad (4b)$$

and $\cos\omega = (\epsilon_2 \cdot \epsilon_1)/\eta$, $u = \theta_1 + \theta - \xi$, $\cos\xi = (\epsilon_2 + \epsilon_1 \cos\theta)/\eta$, and $\eta = \sqrt{(\epsilon_1^2 + \epsilon_2^2 + 2\epsilon_1 \epsilon_2 \cos\theta)}$. The results were binned in kinetic energy E_k and direction cosine $\mu = p_z/p$.

RESULTS AND DISCUSSION

In Fig. 2 we show Monte Carlo calculations of the differential energy spectra of positrons produced in collisions of X- and gamma-ray photons, binned in intervals of μ . The temperature of the hot pair cloud is 450 keV, $N_{\text{tot}} = 10^5$, and $r = R = 3 \times 10^7$ cm. As can be seen, the positron spectra are flat below $E_k \approx 1$ MeV and have an exponential turnover above this energy. The rate of positron production is greatest in the range $0 \leq \mu < 0.25$, that is, for those traveling parallel to the plane of the disk. These positrons also have a slightly harder energy spectrum than those produced in other solid angle intervals. This behavior

Fig. 2. Monte Carlo calculations of positron differential energy spectra produced in X-ray and gamma-ray photon-photon interactions. Labels 1, 2, 3, and 4 stand for positrons produced in the intervals $0 \leq \mu < 0.25$, $0.25 \leq \mu < 0.5$, $0.5 \leq \mu < 0.75$, and $0.75 \leq \mu < 1.0$, respectively, where μ is the cosine of the angle that the outgoing positron makes with respect to the z-axis.

reflects the fact that the secondary electrons and positrons roughly maintain the directions of the colliding photons, and that the most energetic collisions are the head-on photon-photon collisions which take place with photons emitted at small angles with respect to the plane of the disk.

We have also repeated the above calculation with parameters appropriate to a 350 keV pair cloud, but now with $r = R = 2.1 \times 10^7$ cm. We find pair production rates of 1.8×10^{41} and 2.6×10^{41} e^+ /sec at $kT = 350$ and 450 keV, respectively. If these pairs rapidly slow down and annihilate in a cool medium, the maximum annihilation line luminosity that could be expected is $\sim 2 \times 10^{35}$ erg/s. This represents $\sim 1\%$ of the 400 keV - 1.5 MeV luminosity in the γ_1 state, and would yield a specific 511 keV photon flux at Earth $< 3 \times 10^{-4}$ photons/cm²-s-keV, using a line width of ~ 1 keV. This flux is above the limit of the threshold of the HEAO-3 Gamma-Ray Spectrometer, but reflects the overestimates of the pair production rate from X-ray and gamma-ray interactions discussed earlier. The narrow annihilation line luminosity in the direction of Cygnus X-1 during the γ_1 state period has not yet been reported. During the γ_2 state, the reported 3σ upper limit is 3×10^{-4} photons/cm²-s (J. Ling; these proceedings). This flux cannot, however, be compared to the results of this calculation. We leave to further work to determine whether this mechanism could provide the $\sim 4 \times 10^{43}$ e^+ /sec (Lingenfelter and Ramaty 1983) needed to explain the HEAO-3 observations of the narrow galactic center annihilation line in the fall of 1979, if one models the galactic center gamma radiation in a manner similar to our model for Cyg X-1. Should the mechanisms suggested here provide insufficient positron production compared to the observed annihilation line luminosity of the Galactic Center, one would be required to invoke additional escape from the central hot pair cloud.

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