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A Model for the Diffuse γ-Ray Spectrum

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ABSTRACT

A model is proposed to describe the observed shelf in the cosmic diffuse radiation spectrum just above 1 MeV. This model is based on induced positronium annihilation, which at incident photon energy 2 mc^2 gives rise to enhancement of the radiative field. It is proposed that this amplification may occur in double radio sources or other accreting objects. Recent observation of γ-ray line emission from the double radio source SS 433 at 1.2 and 1.5 MeV is in good agreement with the proposed model.

I. INTRODUCTION

It is believed that the lobes of double radio sources contain a continually regenerated electron-positron plasma. This explains the anomalously small Faraday rotation of experimentally observed radiation from the central region.[1] It is further argued that such sources contain a black hole at the center of an accreting disk.[2,3] Electron-positron showers are continuously produced in jets near the inner lobe, travel outward and eventually are annihilated in the outer lobes (providing they have not already done so on the outward journey). The jet-like structure of such sources has been observed in the radio map of the double radio source 3C449.[4,5]

The electron-positron plasma in the outer lobes is relatively cold and approximately 80% of electrons and positrons form positronium.[1,6] It will be shown that a flux of 1MeV photons passing through such a plasma may be enhanced by induced two-photon decay of positronium providing the positronium density exceeds a certain value. Whereas photons of all frequencies are produced in the inner lobe by synchrotron emission of electrons and positrons in their outward motion, only the 1MeV photons are enhanced by the process described herein.

II. ANALYSIS

Consider that a photon of frequency ω and wavelength λ interacts with a positronium atom at rest and annihilates it to yield two photons of frequency ω_1 and ω_2. These photons emerge at angles θ_1 and θ_2 respectively, with respect to the incident photon direction. Taking the positronium atom to be a particle of mass 2m (m is electron mass), a simple Compton-like calculation yields the following relation for the wavelength λ_1,

$$\lambda_1 - \lambda = \lambda_C \left[\sin^2 \frac{\theta_1}{2} - \frac{\lambda_1 \lambda}{\lambda_C^2} \right] \quad (1)$$

where $\lambda_C = h/mc$, is the Compton wavelength, h is Planck's constant and c is the speed of light. Conservation equations indicate that when $\hbar\omega = 2mc^2$ and $\theta_1 = 60°$,

$$\omega = \omega_1 = \omega_2 \quad (2)$$

corresponding to

$$\hbar\omega = 2\hbar\omega_C = 1 \text{ MeV} \quad (3)$$

The equal-frequency photons of (2) emerge at 120° to each other. These photons in turn can induce two other positronium atoms to annihilate to yield two photons each with energy 1MeV. Thus, after two path lengths, an incident flux of 1 MeV photons will be doubled. Hence, for a continually regenerated electron-positron plasma of extension ℓ_p, greater than the mean free path of the 1 MeV photon in the plasma, an incident flux of such photons may be amplified by this process. It should be born in mind that such amplification would likely be diminished due to pair production.[6] However, we also note that such pair production would serve to maintain the rapidly decaying positronium density.

A full quantum electrodynamical calculation for the photon-induced annihilation of positronium yields (1) and the following cross section as a function of incident photon frequency[7]

$$\sigma(\omega) = \pi\alpha^4 r_0^2 f(\xi) \quad (4)$$

Here r_0 is the classical electron radius, α is the fine structure constant and ξ is the dimensionless parameter, $\hbar\omega/mc^2$. The function $f(\xi)$ is given by the following monotonically decreasing expression:

$$f(\xi) = \frac{1}{\xi^4(\xi+2)^3} [\xi(\xi+2)(2\xi^3+7\xi^2+12\xi+8) - 2(\xi+1)(5\xi^2+12\xi+8)\ell n(\xi+1)] \quad (5)$$

In the preceding analysis we refer to the positronium atom in the triplet state as dictated by the principle of charge conjugation invariance when the atom undergoes induced annihilation.

The said proliferation of 1 MeV photons occurs at scattering into 60° about the incident 1 MeV photon beam. For order-of-magnitude estimates we may take the differential cross section to be given by its isotropic form:

$$d\sigma/d\Omega \simeq \sigma(\omega)/4\pi \tag{6}$$

A typical double radio source[4] is of size $\ell_p \simeq 1$ Mpc. Hence it can act as a source of 1 MeV photons if the mean electron-positron density exceeds $1/\ell_p\sigma(2\omega_C) \simeq 10^9$ cm^{-3}. In obtaining this value we have used the preceding three formulas. The electron-positron densities in such objects can vary anywhere between 10^{14} cm^{-3} in the inner region to 10^{-3} cm^{-3} in the outer lobes.[1,8]

However we note that the energy contained in a lobe of density $\simeq 10^9$ cm^{-3} is unrealistically large. Thus, for example, the volume of a lobe of length g and half apex angle θ_o is

$$V \simeq \frac{\pi}{3} g^3 \tan^2\theta_o \simeq g^3\theta_o^2 \tag{7}$$

The energy in this lobe, containing n_c pairs/cm^3 is

$$\begin{aligned} E_o &\simeq 2mc^2 n_c V \\ E_o &\simeq 2mc^2 n_c g^3 \theta_o^2 \end{aligned} \tag{8}$$

With $n_c \simeq 10^9$ cm^{-3} and $\theta_o = 5° = 0.1$ radian, we find $E_o \simeq 10^{73}$ erg.

To remedy this situation it is proposed that the critical density lie within a filamentary cone of apex angle $\theta \simeq 0.01° \approx 2\times10^{-4}$ radian. The energy in this cone is

$$E = E_o\,(\theta/\theta_o)^2 \simeq 10^{67} \text{ erg} \tag{9}$$

Whereas this energy is still not entirely realistic, it renders the proposed scheme somewhat more plausible.

For configurations wherein the positronium plasma moves outward from the central region, it is found that the x-ray spectrum is shifted to higher values. Our peculiar frequency then becomes

6) $$\omega' = 2\omega_C\left[1 + b\,\frac{kT}{mc^2}\right] \tag{10}$$

where the constant $b \simeq 1$ and kT represents the mean kinetic energy of the advancing plasma.[9] For $kT \simeq mc^2$, $\omega' \simeq 2$ MeV. In general, the line-width for a non-Maxwellian plasma is given by[10]

$$\Delta E = 0.97\ (kT \text{ in eV})^{1/2} \text{keV} \qquad (11)$$

which for $kT = mc^2$ gives $\Delta E \simeq 0.7$ MeV.

If one assumes that the diffuse gamma radiation in the universe partially stems from a random distribution of such objects as double radio sources, pulsars, etc., then one would expect the diffuse radiation to exhibit a shelf just above 1 MeV. This shelf has been clearly revealed in an extensive review article of previous observational data by Fichtel et al.[11]

Recently Lamb et al.[12] observed γ-ray line emission from the double radio source SS 433 at 1.2 and 1.5 MeV. These lines can be explained in this model as shifts in the 1 MeV line due to outward motion of the relativistic jets. First we write

$$kT = (\gamma - 1)mc^2$$
$$\gamma \equiv 1/\sqrt{1-(\bar{v}/c)^2} \qquad (12)$$

where $\bar{v}$ represents the mean velocity of the relativistic jet. Substituting these expressions into (10) and setting $\bar{v} = 0.5$ c gives $\omega' \simeq 1.2$ MeV. If we assume a secondary jet with $\bar{v} = 0.75$ c, then (10) gives $\omega' = 1.5$ MeV. Line widths calculated from (11) give $\Delta E/\hbar\omega' \simeq 20\%$ for both lines which agrees with observation to within a factor of 10.

In summary, a model has been proposed based on stimulated annihilation of positronium to explain the shelf in the diffuse γ-ray spectrum just above 1 MeV. Specific application of the model to the double radio source SS 433 was found to be in good agreement with observed spectral emission.

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