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COMMENT ON "TeV CERENKOV EVENTS AS BOSE-EINSTEIN GAMMA CONDENSATIONS"

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ABSTRACT

The idea that the TeV air showers, thought to be produced by gamma rays greater than 10 TeV from Markarian 501, can be mimicked by coherent bunches of sub-TeV photons is reexamined, focusing on fundamental considerations. In particular, it is shown that the minimum spot size of a beam of photons arriving at Earth is on the order of a few kilometers unless a lens with certain characteristics is placed between the TeV laser and Earth. The viability of the production mechanism of coherent bunches of TeV photons proposed by M. Harwit et al. is also reassessed.

Subject headings: BL Lacertae objects: individual (Markarian 501) — gamma rays: theory — infrared: general — masers

It has been argued recently (e.g., Coppi & Aharonian 1999) that the detection of TeV photons from Markarian 501 at energies above 10 TeV (Hayashida et al. 1998; Aharonian et al. 1999) places severe constraints on the diffuse extragalactic IR background and may be particularly problematic (Protheroe & Meyer 2000) in view of recent determinations of the IR background by various experiments. Motivated by this consideration, Harwit, Protheroe, & Biermann (1999) proposed that the observed air showers, which are commonly interpreted as due to single, greater than 10 TeV gamma rays, can be produced by coherent bunches of sub-TeV photons that are not absorbed by pair production on the extragalactic IR background and that when interacting with the Earth's atmosphere could mimic a TeV air shower event. Such bunching can be achieved in principle by a pulsed TeV source (or collection of such sources) with appropriate pulse duration and average intensity (or duty cycle), provided the spot size of the beam illuminating Earth is unresolved by current TeV experiments. However, even if these requirements are not fulfilled (e.g., if the beam spot size is large or if the radiation source is quasi-steady), clumping of photons can be accomplished through Bose-Einstein condensation (i.e., highly occupied states), as proposed by Harwit et al. (1999), provided the intensity of the TeV source is high enough to allow a high occupation number of TeV states. The hypothesis that air showers are due to TeV bunches has been tested subsequently by the HEGRA collaboration (Aharonian et al. 2000), who claimed that it can be rejected on the basis of a comparison of the energy-dependent penetration depth in Earth's atmosphere of TeV photons from Mrk 501 with the penetration depth of photons from the Crab Nebula. In view of the growing interest in this scenario, it is worth reexamining its viability. Below, we discuss the fundamental limitations of such a TeV laser.

The basic requirements for the system under consideration are as follows:

1. A typical Cerenkov flash produced by a TeV air shower lasts for about several nanoseconds. This implies that the width of the TeV pulse produced by the laser, Δt, should not exceed this timescale and that temporal coherence must be maintained over a time greater than Δt. The corresponding light crossing time, $c\Delta t$, is on the order of several meters. In principle, however, the dimension of the system should not be restricted to this scale. In laboratory lasers, for instance, pulse durations as short as the decay time of the lasing substrate (which can be shorter by many orders of magnitude than the light crossing time of the cavity although typically larger than the beam diameter) can be achieved using, e.g., mode-locking or *Q*-switching methods (which require modulation of either the pumping rate or the refraction index in the cavity; e.g., Svelto 1998). Although it is difficult to envisage how this situation can be accomplished under astrophysical conditions, the requirement that the size of the system would not exceed the pulse width does not seem to be fundamental. Moreover, if the laser mechanism involves relativistic motion, the pulse can be further compressed owing to time dilation effects.
2. The spot size of each bunch of TeV photons impinging on Earth should be within the angular resolution of current TeV experiments; otherwise the shower image will differ from that expected to be produced by a single TeV photon. (If the spot is resolved, it can give rise to a shower image that may resemble that of a cosmic-ray shower. Such an event is likely to be rejected.) For a typical angular resolution of $0\overset{\circ}{.}1$ and shower height of, say, 10 km, this yields a spot size less than 20 m. As shown below, this requirement places a stringent constraint on the system.
3. The intensity of the TeV source should be consistent with the average flux observed at Earth.

Is it possible that the TeV air showers are produced by a pulsed TeV source with an unresolved beam? Consider some apparatus that produces a pulsed TeV beam having a diameter D at the beam waist (see Fig. 1). The diffraction angle of the beam is $\psi = \lambda/D$, where $\lambda = 1.25 \times 10^{-16}(\epsilon/1\ \mathrm{TeV})^{-1}$ cm is the wavelength of the laser at its spectral peak and ϵ is the corresponding energy. At a distance L from the source, the beam spot size a is the sum of the waist spot size and the size of the diffraction wing:

$$a = D + \psi L = D + (\lambda/D)L. \tag{1}$$

For a target at a fixed distance L from the laser, the minimum beam spot size $a_{\min}$ can be obtained by minimizing a with respect to D, that is, taking $da/dD = 0$. This yields $D =$

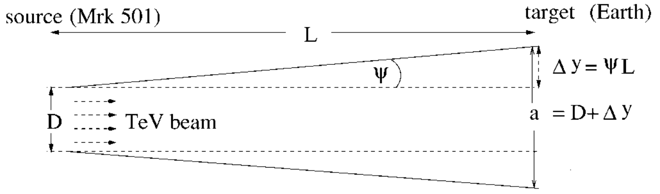

FIG. 1.—Schematic illustration of the propagation of a coherent TeV beam having a diameter D at its waist. The diffraction angle of the beam is $\psi = \lambda/D$, where λ is the corresponding wavelength, and the beam spot size a distance L away is $a = D + \psi L$.

$\sqrt{\lambda L}$ and

$$a_{\min} = 2\sqrt{\lambda L} \simeq 4 \times 10^{5}(L/100\ \mathrm{Mpc})^{1/2} \times (\epsilon/1\ \mathrm{TeV})^{-1/2}\ \mathrm{cm}. \qquad (2)$$

Taking L to be the distance from Earth to Mrk 501 ($L = 130$ Mpc assuming $h_0 = 0.65$), we conclude that the arriving pulse of sub-TeV photons would spread over a distance of at least several kilometers.

The spot size can in principle be reduced if a lens is placed between the source and Earth. In the optimal case, the radius of the lens should be comparable to the beam radius and its focal plan should intersect Earth. Under such conditions, the size of the spot illuminated by the TeV laser is diffraction-limited (assuming complete coherence). Denoting by D_l the lens diameter and by L_l its distance from Earth, and requiring a spot size smaller than, say, 20 m, yields a minimum lens diameter of

$$D_{l_{\min}} \simeq 10^{7}(L_l/100\ \mathrm{Mpc})(\epsilon/1\ \mathrm{TeV})^{-1}\ \mathrm{cm}. \qquad (3)$$

This is larger than the gravitational radius of a stellar mass object. As an illustrative example consider lensing of the TeV beam by a point mass located on the axis of the beam a distance L_l from Earth. In that case, only rays for which the impact parameter lies in the range between b_+ and b_-, where $b_\pm \simeq 2\,(r_g L_l)^{1/2} \pm d$, where d is the maximum allowed diameter of the beam spot on Earth and r_g is the gravitational radius of the lens, will be deflected by the required angle. For typical parameters, we find that only a small fraction of the flux will be amplified and, therefore, a point mass cannot provide the required lens. What seems to be needed is some extended object with a density profile such that the refraction index of the lens would be independent of the lens radius. Perhaps high-velocity clouds?

As mentioned above, if the intensity of the radiation source is sufficiently high, then it is conceivable that coherent bunches of photons with a spatial dimension on the order of a phase cell will arrive at the detector, regardless of the beam size. This is the essence of the interesting proposal by Harwit et al. (1999). We therefore examine the constraints on the parameters of a TeV source imposed by the requirement that the occupation number of arriving TeV photons exceeds unity (in which case the fluctuation can be well above normal). Consider a beam of photons emanating from some radiation source and falling on a detector having an area A and response time τ, and denote by $\langle N\rangle$ and g, respectively, the average number of photons incident on the detector and the number of phase cells in the phase volume occupied by these photons (i.e., $\langle N\rangle/g$ is the occupation number). Then the fluctuation in the number of photons in the beam can be expressed as (Harwit 1960)

$$\langle(\Delta N)^2\rangle = \langle N^2\rangle - \langle N\rangle^2 = \langle N\rangle(1 + \langle N\rangle/g). \qquad (4)$$

The first term on the right-hand side corresponds to the photon shot noise, and the second represents the clumping of highly occupied states. Now, the number of phase cells can be expressed as (Harwit 1960)

$$g = (A\tau c)2\Omega\nu_0^2\Delta\nu/c^3, \qquad (5)$$

where ν_0 is the central frequency of the photon beam, $\Delta\nu$ is the spectral bandwidth, and Ω is the solid angle occupied by the k-vectors of the arriving photons. Note that, in the case of an isotropic radiation source, Ω is simply the solid angle subtended by the source at the detector. However, Ω can in principle be much smaller if the source is highly beamed.

Fluctuation well in excess of the shot noise will occur when $\langle N\rangle/g \gg 1$. This implies a photon flux at the detector,

$$\mathcal{F} \simeq \langle N\rangle/(\tau A) \gg 2\Omega\lambda_0^{-2}\Delta\nu, \qquad (6)$$

where λ_0 is the corresponding wavelength. For a beam of TeV photons, this yields

$$\mathcal{F} \gg 10^{32}(\epsilon/1\ \mathrm{TeV})^{2}\Omega\Delta\nu\ \mathrm{cm^{-2}\ s^{-1}}. \qquad (7)$$

Note that, for a quasi-steady source, this is roughly the average flux at the detector. Equating equation (7) with the observed flux from Mrk 501, which in its high state is $\sim 10^{-10}\ \mathrm{cm^{-2}\ s^{-1}}$ (e.g., Pian et al. 1998), yields

$$\Omega\Delta\nu < 10^{-42}\ \mathrm{Hz}. \qquad (8)$$

For a source dimension $\sim 3 \times 10^{13}(M/10^{8}\ M_\odot)$ cm, as adopted by Harwit et al. (1999), we find $\Omega \sim 10^{-26}$, implying $\Delta\nu/\nu_0 < 10^{-42.5}\ (\epsilon/1\ \mathrm{TeV})^{-1}\ (10^{8}\ M_\odot/\mathrm{M})^{2}$. The radiation source can, however, be smaller. The solid angle subtended by the smallest possible radiation source for which the spread due to diffraction is still within the angular resolution of a typical TeV telescope is $\Omega \sim \lambda_0^2/A \sim 10^{-38.5}$, where $A \sim 4 \times 10^{6}\ \mathrm{cm^2}$ is the area of the largest unresolved spot. In this case $\Delta\nu/\nu_0 < 10^{-30}$ is required. The requirement imposed on the spectral bandwidth may be less stringent if the TeV radiation is beamed into a solid angle much smaller than that subtended by the source.

We conclude by briefly commenting on the TeV laser production mechanism discussed by Harwit et al. (1999). These authors suggested that inverse Compton scattering of OH or H_2O megamaser photons by a relativistic jet of nonthermal (in the comoving frame) electrons may provide the means for producing coherent TeV states. Let n_s be the total number density of maser photons, as measured in the rest frame of the jet, and denote by ν_s and $\Delta\nu_s$, respectively, the comoving central frequency and bandwidth of the seed (maser) photons. Then the occupation number of the maser photons (which is a Lorentz invariant) can be expressed as $N_{\mathrm{occ}} = n_s/(2\nu_s^2\Delta\nu_s\Delta\Omega_s/c^3)$, where $\Delta\Omega_s$ is solid angle of the maser beam as measured in the jet frame. Likewise, the occupation number of the scattered photons is given by $N_{\mathrm{occ}}^{\mathrm{scat}} = n_\gamma/(2\nu_\gamma^2\Delta\nu_\gamma\Delta\Omega_\gamma/c^3)$, where again all quantities are measured in the comoving frame. Now the number density of scattered photons is given approximately by $n_\gamma \simeq \tau n_s$, with τ being the optical depth along the jet. Consequently, $N_{\mathrm{occ}}^{\mathrm{scat}}/N_{\mathrm{occ}} \simeq \tau(\Delta\nu_s/\Delta\nu_\gamma)(\Delta\Omega_s/\Delta\Omega_\gamma)(\nu_s/\nu_\gamma)^2$. For a maser frequency $\nu_s = 22$ GHz and gamma-ray energy of 1 TeV, this is smaller by a factor $(\Delta\Omega_\gamma/\Delta\Omega_s)(\nu_\gamma/\nu_s)^3 > 10^{48}\Gamma^{-6}$ than the ratio of occupation numbers estimated by Harwit et al. (1999). Note that, since the electron distribution is isotropic in the rest frame of the jet, $(\Delta\Omega_\gamma/\Delta\Omega_s) > 1$.

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