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, 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.

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, $\Delta t$, should not exceed this timescale and that temporal coherence must be maintained over a time greater than $\Delta t$. 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 $\theta < 1$ 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 $\lambda = 1.25 \times 10^{-6}(e/1 \text{ TeV})^{-1} \text{ cm}$ is the wavelength of the laser at its spectral peak and $e$ 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:

$$a = D + \psi L = D + (\lambda/D)L. \quad (1)$$

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 $D = \frac{L}{\pi}$.
the fluctuation in the number of photons emanating from some radiation source and falling on the detector and the number of phase cells in the phase volume occupied by these photons (i.e., \(N/g\) is the occupation number). Then the fluctuation in the number of photons in the beam can be expressed as (Harwit 1960)

\[
\langle (\Delta N)^2 \rangle = \langle N^2 \rangle - \langle N \rangle^2 = \langle N \rangle(1 + \langle N/g \rangle).
\]

(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)

\[
g = (\text{Arc})2\Omega v_0 \Delta \nu c^3,
\]

(5)

where \(v_0\) is the central frequency of the photon beam, \(\Delta \nu\) is the spectral bandwidth, and \(\Omega\) is the solid angle occupied by the \(k\)-vectors of the arriving photons. Note that, in the case of an isotropic radiation source, \(\Omega\) is simply the solid angle subtended by the source at the detector. However, \(\Omega\) cannot be much smaller if the source is highly beamed.

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

\[
\mathcal{T} \equiv \langle N \rangle/(\pi A) \gg 2\Omega c^2 \Delta \nu
\]

(6)

where \(\lambda_0\) is the corresponding wavelength. For a beam of TeV photons, this yields

\[
\mathcal{T} \gg 10^{-12}(\epsilon/1 \text{ TeV})^2 \Omega_c \Delta \nu \text{ cm}^{-2} \text{ s}^{-1}.
\]

(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 \(\sim 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}\) (e.g., Pian et al. 1998), yields

\[
\Omega \Delta \nu < 10^{-42} \text{ Hz}
\]

(8)

For a source dimension \(\sim 3 \times 10^{19}(M/10^5 M_\odot)\) cm, as adopted by Harwit et al. (1999), we find \(\Omega \sim 10^{-26}\), implying \(\Delta \nu v_0 < 10^{-42.5} (\epsilon/1 \text{ TeV})^{-1} (10^5 M_\odot/M)^2\). 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 \(\Omega \sim \lambda_0^2/A \sim 10^{-30.5}\), where \(A \sim 4 \times 10^6 \text{ cm}^2\) is the area of the largest unresolved spot. In this case \(\Delta \nu v_0 < 10^{-39}\) 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$_2$O 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 \(\nu_s\) 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 \(N_{\nu,0} = n_s/(2\pi \Delta \nu_s \Delta \Omega, c^{-1})\), 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 \(N_{\nu,sc}/N_{\nu,0} = \tau(\Delta \nu_s/\Delta \nu_r)/(\Delta \Omega_s/\Delta \Omega_r)(\nu_s/\nu_r)^3\), where \(\tau\) again all quantities are measured in the comoving frame. Now the number density of scattered photons is given approximately by \(n_s \tau\), with \(\tau\) being the optical depth along the jet. Consequently, \(N_{\nu,sc}/N_{\nu,0} = \tau(\Delta \nu_s/\Delta \nu_r)/(\Delta \Omega_s/\Delta \Omega_r)(\nu_s/\nu_r)^3\). For a maser frequency \(\nu_s = 22 \text{ GHz}\) and gamma-ray energy of 1 TeV, this is smaller by a factor \((\Delta \Omega_s/\Delta \Omega_r)(\nu_s/\nu_s)^3 > 10^{46}\) 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, $(\Delta \Omega_\gamma / \Delta \Omega_e) > 1$.

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