

TeV CERENKOV EVENTS AS BOSE-EINSTEIN GAMMA CONDENSATIONS

MARTIN HARWIT,¹ R. J. PROTHEROE,² AND P. L. BIERMANN^{3,4}

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ABSTRACT

The recent detection of gamma radiation from Mrk 501 at energies as high as ~ 25 TeV suggests stringent upper bounds on the diffuse, far-infrared, extragalactic radiation density. The production of electron-positron pairs through photon-photon collisions would prevent gamma photons of substantially higher energies from reaching us across distances of order 100 Mpc. However, coherently arriving TeV or sub-TeV gamma rays—Bose-Einstein condensations of photons at these energies—could mimic the Cerenkov shower signatures of extremely energetic gamma rays. To better understand such events, we describe their observational traits and discuss how they might be generated.

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

1. INTRODUCTION

High-energy gamma rays are readily absorbed in the intergalactic medium through pair production in a sufficiently dense, diffuse, microwave or infrared radiation field (Gould & Schröder 1966; Stecker, De Jager, & Salamon 1992). For this reason, a great deal of attention has been paid to gamma rays at energies apparently reaching ≥ 10 TeV, recently detected from the galaxy Mrk 501 (Hayashida et al. 1998; Pian et al. 1998; Aharonian et al. 1999; Krennrich et al. 1999). Mrk 501 is a BL Lac object at a distance of ~ 200 Mpc, for a Hubble constant $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Unattenuated transmission of ≥ 10 TeV photons across distances of this order would place severe constraints on the diffuse extragalactic infrared background radiation (Coppi & Aharonian 1997; Stanev & Franceschini 1998), placing upper limits to the radiation density that are close to values derived from *COBE* detections and *IRAS* source counts alone (Hauser et al. 1998; Hacking & Soifer 1991; Gregorich et al. 1995). Given these close coincidences, it is useful to reexamine the severity that these observations place on the density of the diffuse extragalactic infrared radiation (DEIR).

2. BOSE-EINSTEIN CONDENSATIONS OF PHOTONS

Highly excited quantum oscillators, i.e., coherent radiation, can be produced in a variety of processes and are regular components of blackbody radiation in the Rayleigh-Jeans tail of the energy distribution. These excited oscillators correspond to densely occupied radiation phase cells—a Bose-Einstein condensation of photons all having quantum mechanically indistinguishable properties, i.e., identical momenta, positions, polarizations, and directions of propagation, within the Heisenberg uncertainty constraints.

Given that cosmic-ray particles can have energies going up to 3×10^{20} eV, and given that one expects a cutoff for gamma rays from Mrk 501 at energies many orders of magnitude lower, around 10 or 20 TeV, it does not seem far-fetched to think that the actually observed gamma rays reaching Earth might lie far

out in the low-frequency tail of some significantly more energetic radiation field characterized by an equivalent temperature much higher than a few TeV.

If this were the case, we would expect that the radiation arriving at Earth could be highly coherent, meaning that phase cells would be filled to rather high occupation numbers N . As they interact with the DEIR, densely filled phase cells can decline in population and lose energy only by going stepwise from an initial occupation number N to $(N - 1)$, and from there to $(N - 2)$, etc. Because the mean free path for interactions of photons with the DEIR is energy dependent, a fraction of a coherent assembly of photons could penetrate appreciably greater distances through the diffuse extragalactic radiation field than, say, a single photon of the same total energy.

A number N_a of such arriving photons, each with energy $h\nu$, would impinge on the Earth's atmosphere at precisely the same instant and would interact with the atmosphere, producing an air shower that emits Cerenkov light that could mimic that due to a single photon with energy $N_a h\nu$ impinging on the atmosphere. These two kinds of impacts could be distinguished by shower images they produce and probably also by the fluctuations in the energy distribution observed near the cutoff energy E_{CO} for a series of Cerenkov events.

Because of their high momenta, the arriving bunched photons would spread over only the smallest distance Δy in their traversal through extragalactic space, given by the uncertainty relation $\Delta p_y \Delta y \sim h$. Here Δp_y , the uncertainty in transverse momentum, is the product of the photon momentum $h\nu/c$ and the angular size that the source subtends at Earth. The smallest dimension we could expect would be of the order of an active galactic nucleus (AGN) black hole Schwarzschild radius $\sim 3 \times 10^{13} M/(10^8 M_\odot)$ cm. This would make $\Delta y \sim (10^8 M_\odot/M)10^{-3}$ cm—negligible in Cerenkov detection.

3. INTERPRETATION OF CERENKOV RADIATION DATA

TeV γ -rays are detected through the Cerenkov radiation generated in the Earth's atmosphere by electrons in an "air shower" initiated by the γ -ray. Such air showers are electromagnetic cascades involving pair production and bremsstrahlung interactions. As long as the energy of the photon entering the atmosphere is sufficiently high, the Cerenkov yield of the air shower is sensitive primarily to the total energy deposited, not to the number of instantaneously arriving photons. Accordingly, one might expect such telescopes to mistakenly record

¹ 511 H Street SW, Washington DC 20024-2725; also Cornell University.

² Department of Physics and Mathematical Physics, University of Adelaide, SA 5005, Australia.

³ Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany.

⁴ Department of Physics and Astronomy, University of Bonn, Bonn, Germany.

five simultaneously arriving 5 TeV photons as a single shower of 25 TeV. On the other hand, if the number of simultaneously arriving photons N were much higher, then the showers would look very different, and if N were really large there would be no Cerenkov radiation at all.

To quantify the discussion above, we shall compare the mean and standard deviation of the number of electrons in the shower $N_e(t)$ as a function of depth into the atmosphere measured in radiation lengths t for the two cases. Note that the atmosphere is approximately 1030 g cm^{-2} thick and the radiation length of air including forward scattering is 36.66 g cm^{-2} . Although the cross section for interaction of an assembly of N coherent photons is N times higher than that of an individual photon, a shower initiated by an assembly of N coherent photons having total energy $N\epsilon$ would be identical to a superposition of N showers due to individual photons of energy ϵ . Above $\sim 3 \text{ GeV}$ the pair production mean free path for photons in air is constant at $t_{\text{pair}} = 9/7$ radiation lengths. For an assembly of N coherent photons, the pair production mean free path is therefore identical to an exponential distribution with mean $t_{\text{pair}} = (9/7)$, i.e., it is the same as the distribution of first interaction points of a single photon. This also implies that at depth t the average number of photons remaining in the assembly is $N \exp(-t/t_{\text{pair}})$.

Crewther & Protheroe (1990) provide a parametrization of the distribution of the number of electrons in photon-initiated showers $p[N_e(t - t_1)]$ as a function of depth into the atmosphere beyond the first interaction points of the primary photons ($t - t_1$). We use their results together with our Monte Carlo simulation of the first interaction points of each of the N photons in a coherent assembly to simulate the development of the air shower due to the coherent assembly, thus taking account of all fluctuations in shower development. In Figure 1 we show as a function of atmospheric depth t N_e and $N_e \pm 1 \sigma$ based on 1000 simulations for the case of single photons of energy 25 GeV, assemblies of five coherent photons each having energy 5 TeV, and assemblies of 25 coherent photons each having energy 1 TeV (each assembly has energy 25 GeV). As can be seen, air showers due to coherent assemblies develop higher in the atmosphere and have much smaller fluctuations in shower development. Such differences between showers due to single photons and assemblies of coherent photons would produce different Cerenkov light signatures and should be detectable with state-of-the-art Cerenkov telescopes such as HEGRA (see, e.g., Konopelko et al. 1999).

4. EXTRAGALACTIC OPTICAL DEPTH

Propagation of assemblies of N_0 coherent photons each of energy ϵ through the microwave and DEIR fields is analogous to their propagation through the atmosphere. However, assemblies of coherent photons having total energy $E_{\text{tot}} = N_0\epsilon$ may travel farther than single photons of energy $N_0\epsilon$ without interaction because, unlike in the atmosphere, the mean free path for pair production in the extragalactic radiation fields depends strongly on photon energy.

Just as in the air-shower cascade, only a single photon at a time can be lost from a phase cell, with a corresponding decline in occupation number from N to $N - 1$. On each encounter with an infrared photon, the coherent assembly of N photons has an N -fold increase in probability for some photon to be removed, so the mean free path is $x_{\text{pair}}(\epsilon)/N$, where $x_{\text{pair}}(\epsilon)$ is the mean free path for photon-photon pair production by single photons of energy ϵ through the extragalactic radiation fields.

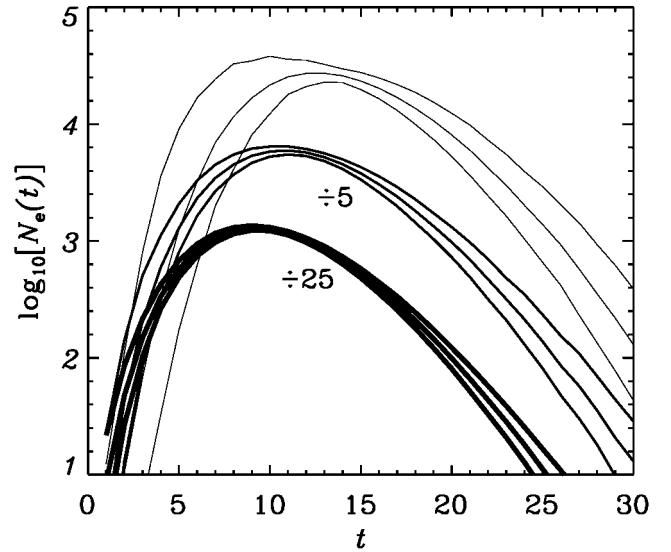


FIG. 1.—Number of electrons N_e in the air shower versus depth in the atmosphere measured in radiation lengths. The top three curves show N_e and $N_e \pm 1 \sigma$ for single photons of energy 25 TeV, the middle three curves show N_e and $N_e \pm 1 \sigma$ for an assembly of five coherent photons each of energy 5 TeV (note these curves have been displaced down by a factor of 5 to avoid confusion), and the bottom three curves correspond to an assembly of 25 coherent photons each of energy 1 TeV (displaced down by a factor of 25).

This implies that at distance x from the source the average number of photons remaining in the assembly is $N_R(x) = N_0 \exp[-x/x_{\text{pair}}(\epsilon)]$, precisely the expression that would hold for N_0 independent photons. If d is the distance from the source to Earth, then the energy observable by Cerenkov telescopes is $E_{\text{obs}} = N_R(d)\epsilon$, and the number of photons in the assembly of coherent photons on emission was $N_0 = N_R \exp[d/x_{\text{pair}} \times (E_{\text{obs}}/N_R)]$. For the purpose of illustration, we use for $x_{\text{pair}}(E)$ the logarithmic mean of the upper and lower curves of Figure 1a of Bednarek & Protheroe (1999), which is based on the infrared background models of Malkan & Stecker (1998). We show in Figure 2 the result for propagation of coherent photons through the microwave and DEIR fields across $d = 200 \text{ Mpc}$ appropriate to Mrk 501. We note, for example, that a coherent assembly of forty 10 TeV photons emitted would typically arrive at Earth as a coherent assembly of ten 10 TeV photons with an observable energy of 100 TeV, while a single photon of 100 TeV would have a probability of much less than 10^{-6} of reaching Earth.

5. FLUCTUATIONS IN THE ARRIVING PHASE CELL ENERGY CONTENT

A stream of photons characterized by a brightness temperature T_b of necessity will also have a distribution of phase cell occupation numbers N , which for high average values $\langle N \rangle$ fluctuates as $(\Delta N)_{\text{rms}} \sim \langle N \rangle$. For emission of a stream of identical assemblies of coherent photons, each containing N_0 photons on emission, fluctuations in the number of photons N_R remaining in each assembly after propagation to Earth through the DEIR are Poissonian about the mean value $\langle N_R \rangle$, i.e., $(\Delta N)_{\text{rms}} \approx \langle N_R \rangle^{1/2}$, for $\langle N_R \rangle \ll N_0$, and less than Poissonian for $N_R \sim N_0$. Both of these effects broaden the energy distributions of observed Cerenkov events.

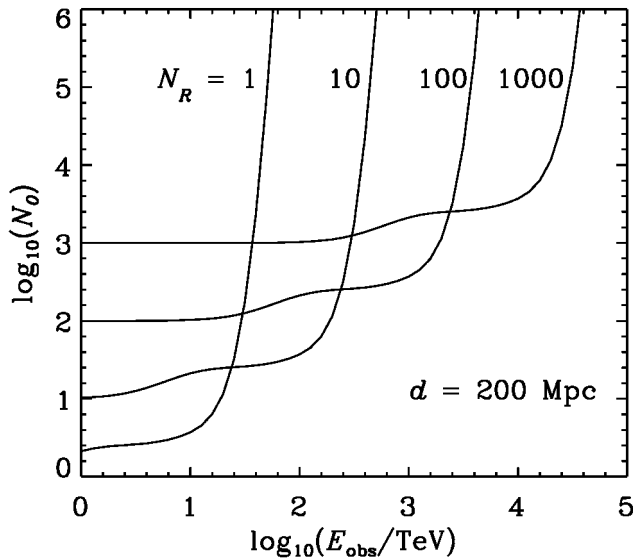


FIG. 2.—Propagation of coherent photons across 200 Mpc through the microwave and diffuse infrared extragalactic radiation fields. N_0 is the number of photons in the coherent assembly emitted in our direction. N_R is the surviving number. E_{obs} is the energy of the observed Cerenkov event, equivalent to $N_R \epsilon$, where ϵ is the energy of individual photons in the assembly.

6. WHAT MECHANISMS COULD PRODUCE COHERENT TeV GAMMAS?

In the laboratory (such as Deutsches Elektronen-Synchrotron [DESY]), coherent X-radiation can be produced by stimulated emission of relativistic electrons through a periodically varying magnetic field (Madey 1971). Therefore, this shows that such processes are available in principle.

A more promising astrophysical process might arise from the interaction of a collimated beam of relativistic electrons moving roughly upstream against an OH or H₂O megamaser. This process is attractive because a substantial number of AGNs are known to have nuclear megamasers. Inverse Compton scattering would produce photons with an energy increase γ^2 in the comoving frame of the jet of relativistic, randomly directed electrons. Here γ is the Lorentz factor of electrons in the jet's comoving frame. To produce 1 TeV photons from H₂O megamaser radiation at 22 GHz, we would require $(\delta\gamma)^2 \sim 1.1 \times 10^{16} (E/\text{TeV})$, where $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$ is the Doppler factor, $\beta = v/c$ refers to the relativistic bulk velocity v , and $\Gamma \equiv [1 - v^2/c^2]^{-1/2}$ is the Lorentz factor of the jet. The factor δ^2 translates the photon's initial energy to the comoving frame and back to the frame of an Earth-based observer. For Mrk 501, the line-of-sight angle θ appears to be directed very nearly in our direction, so we may choose $\delta = 2\Gamma \sim 25$ (e.g., Tavecchio, Maraschi, & Ghisellini 1998).

As shown below, the number of phase cells into which the maser photons can be inverse Compton scattered is limited and quickly fill up for relativistic jets with high column densities. At the photon densities discussed, nonlinear effects can be neglected.

To provide a representative example, we might cite conditions in the galaxy NGC 1052, which contains a water megamaser with components that appear to lie along the direction of a radio jet (Claussen et al. 1998). Although this may just be a projection effect, we will assume as these authors have that it may signify interaction of the jet with dense clumps

of molecular clouds—possibly producing maser activity in shocks.

The observed radiation intensity of the maser per unit bandwidth at 22 GHz is $I(\nu) = [c\rho(\nu)/4\pi] = 50$ mJy for a beam size that is unresolved at 0.3×1 mas. The beam, however, is clearly much larger than the roughly 40 individual sources that are detected by virtue of their different velocities along the line of sight, whose centroids are separated by as little as ~ 0.1 mas. The brightness temperature of these individual sources is $T_b(\nu) \equiv [I(\nu)c^2/2k\nu^2] > 4.5 \times 10^8$ K if the nominal beam size is assumed. The density of phase space cells is $n(\nu) = (8\pi\nu^2/c^3) \sim 4.5 \times 10^{-10} \text{ cm}^{-3} \text{ Hz}^{-1}$ so that the phase cell occupation number becomes $N_{\text{occ}} = [\rho(\nu)/h\nu n(\nu)] = (kT_b/h\nu) > 4.3 \times 10^8$.

All these figures are lower limits, since neither the angular resolution nor the spectral resolution suffice to resolve the individual maser sources. For this reason, it may be better to assume the properties of the better resolved Galactic H₂O masers, which have a brightness temperature of order $T_b \sim 10^{14}$ K and a corresponding occupation number of order $N_{\text{occ}} \sim 10^{14}$ (Moran 1996). To be somewhat more conservative, we will adopt a value of $N_{\text{occ}} \sim 3 \times 10^{13}$ below.

Under a Lorentz transformation $I(\nu)$ and $\rho(\nu)$ scale as ν^3 , as does $h\nu n(\nu)$, so that the phase cell occupation number transforms as a constant. We can therefore deal with the occupation number as though it were in the rest frame of the jet of relativistic electrons. These electrons with energy $\gamma m_e c^2$ will have some velocity dispersion, leading to an energy bandwidth $\Delta\gamma m_e c^2$. On inverse Compton scattering the effective occupation number of scattered photons will be reduced by the ratio of bandwidths, $(\Delta\gamma/\gamma)/(\Delta\nu/\nu)$. If we take $(\Delta\gamma/\gamma) \sim 1$ and $(\Delta\nu/\nu) \sim 3 \times 10^{-6}$ corresponding to a 1 km s⁻¹ velocity spread, the reduction in occupation number is of order 3×10^5 , bringing the actual occupation number down to $\sim 10^8$.

The occupation number of inverse Compton scattered photons also could in principle be diluted by the low, effective cross section for backscatter, i.e., by the Klein-Nishina cross section for backscattering. However, despite the $\gamma\delta$ value of $10^8 (\delta/25) [\gamma/(4 \times 10^6)]$ for electrons, the incident photons only have energy $\gamma h\nu\delta \sim 10^4$ eV in the electron's rest frame, far lower than the 0.511 MeV electron rest mass. The Klein-Nishina cross section, therefore, reduces to the Thomson cross section $\sigma_T \sim 6.6 \times 10^{-25} \text{ cm}^2$.

We can assume that the masers are isotropic or else, if they are not, that there are a larger number than are actually observed. Either way, the scattered light they produce would be the same. If we further assume a jet with relativistic electron column density through which the maser photons pass of order $n_{e,\text{rel}} l \sim 10^{17} \text{ cm}^{-2}$, we can estimate the phase cell occupation number of the scattered radiation. It is the product of the maser beam phase cell occupation number, the ratio of bandwidths, the electron column density, and the Thomson cross section, giving

$$N_{\text{occ}}^{\text{scat}} \sim 6 \left(\frac{N_{\text{occ}}}{3 \times 10^{13}} \right) \left[\frac{(\Delta\nu/\nu)/(\Delta\gamma/\gamma)}{3 \times 10^{-6}} \right] \left(\frac{n_{e,\text{rel}} l}{10^{17} \text{ cm}^{-2}} \right). \quad (1)$$

Interestingly, those phase cells with high backscattered occupation number N_b will increase their occupancy at a rate $(N_b + 1)$ times faster than unoccupied cells, since induced scattering then begins to play a role—there is gain. We may, therefore, expect such a configuration to give rise to reasonably high

occupation numbers for TeV photons and energy densities compatible with observed values. NGC 1052 exhibits nearly 40 maser hot spots, with a total 22 GHz luminosity of $\sim 200 L_{\odot} \sim 8 \times 10^{35}$ ergs s^{-1} . Let us assume that the maser power available for interacting with the relativistic jet would be equivalent to only 25% of this. If only fraction $n_{e,rel} l \sigma_T \sim 6.6 \times 10^{-8}$ of this radiation is scattered but each photon's energy increases by $\sim 1.1 \times 10^{16}$, the 1 TeV luminosity is $\sim 1.5 \times 10^{44}$ ergs s^{-1} . This needs to be compared to the TeV flux from Mrk 501 in its high state, which is of order 3×10^{-10} ergs $cm^{-2} s^{-1}$, corresponding for a distance of 200 Mpc to an apparent omnidirectional luminosity of 1.5×10^{45} ergs s^{-1} (Pian et al. 1998). Since our model assumes only a single jet spherically expanding within a relatively narrow solid cone whose axis is directed at us, these two figures are roughly consonant.

7. SYNCHROTRON EMISSION FROM RELATIVISTIC ELECTRONS

A highly relativistic electron with energy E emits synchrotron power in its rest frame $P(E) \sim 2.6 \times 10^{-4} (B/0.1 \text{ G})^2 \times (\gamma/4 \times 10^6)^2$ ergs s^{-1} .

The peak frequency the photons attain in this frame will be of the order of

$$\nu_m \sim \frac{eB\gamma^2}{2\pi m_e c} \sim 4.5 \times 10^{18} \left(\frac{B}{0.1 \text{ G}} \right) \left(\frac{\gamma}{4 \times 10^6} \right)^2 \text{ Hz}, \quad (2)$$

where m_e is the electron rest mass, $B \sim 0.1 \text{ G}$ (e.g., Bednarek & Protheroe 1999) is the local magnetic field strength, and e is the electron charge. In the terrestrial observer's frame the frequency becomes $\nu_m \delta \sim 10^{20}$ Hz, which roughly corresponds to the peak synchrotron radiation frequency of Mrk 501 in the high state.

OSSE observations during flaring (Catanese et al. 1997) show that the energy flux per log energy interval continues up to ~ 500 keV at roughly the same level as that observed by *BeppoSAX* (Pian et al. 1998), indicating that Mrk 501 emits a synchrotron power at 0.5 MeV comparable to the TeV power during flaring. The emitted synchrotron power in the relativistic jet's comoving frame would be $2.4 \times 10^{42} (25/\delta)^2$ ergs s^{-1} , implying emission from $\sim 10^{46} (25/\delta)^2 (0.1 \text{ G}/B)^2 (4 \times 10^6/\gamma)^2$ relativistic electrons.

In recent models of AGN jet dynamics (e.g., Falcke & Biermann 1999), a relativistic jet can readily interact with N_{cl} dense

ambient molecular clumps located at $\sim 10^{19}$ cm from the central engine to produce relativistic shocks that could trigger maser emission in these clumps. Local acceleration at the shock fronts or production from hadronic interaction and decays could then also provide relativistic particle energies $\gamma m_e c^2 \sim 3.2 (\gamma/4 \times 10^6)$ ergs in the jet's comoving system. The timescale for energy loss for these particles through synchrotron radiation is of order $t_{synch} \sim 1.25 \times 10^4 (4 \times 10^6/\gamma) (0.1 \text{ G}/B)^2$ s. Since the relativistic shocks propagate into the jet at a significant fraction of the speed of light, the radiating postshock volumes have dimensions of order $ct_{synch} \sim 10^{14} - 10^{15}$ cm on a side. At particle densities of order $n_{e,rel} \sim 10^2/N_{cl} \text{ cm}^{-3}$, a postshock column density of 10^{17} cm^{-2} , through the N_{cl} shocks, therefore, appears possible.

8. DISCUSSION

It is possible that highly energetic gamma radiation from distant cosmological sources will be found to appear in conflict with pair production constraints imposed by the diffuse extragalactic infrared background radiation. This apparent violation could then be due to coherent TeV gamma rays of lower energy, whose Cerenkov radiation superficially mimics individual photons of much higher energy. We have suggested how the Cerenkov radiation signatures of coherent and incoherent radiation can be distinguished and have sketched a plausible way in which coherent TeV photons could be astrophysically generated. Whether this particular mechanism is found in nature remains to be determined, but other possible sources of coherent TeV gamma radiation are also entirely possible. If coherent TeV photons can be produced in nature, then we have shown that there exists a mechanism by which multi-TeV Cerenkov signals may be observed from high-redshift sources.

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