Cygnus X-3 and the photinos

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The possibility that the neutral radiation with an energy of 10^{15}–10^{16} eV which has been detected from Cygnus X-3 might be interpreted as a flux of photinos is discussed. Calculations are carried out on the production of photinos in the source through the production and decay of gluinos and on shower production in the earth's atmosphere in the reactions $\tilde{\gamma} + N \to \tilde{\gamma} + X$ and $\tilde{\gamma} + e \to \tilde{e} \to \tilde{\gamma} + e$. The results show that the "photino hypothesis" requires an unacceptably large source luminosity: $L_p \gtrsim 10^{44}$ erg/s.

1. The flux of neutral radiation[1] with $3\times10^{14} \lesssim E \lesssim 10^{16}$ eV from Cygnus X-3 which has been detected is usually interpreted as a flux of γ rays. Although this is a natural interpretation, it runs into three difficulties: First, the extensive air showers from which the radiation has been detected contain too many muons for electromagnetic showers[1], (but see the experimental results of Ref. 1, which require a special discussion); second, the NUSEX[2] and Soudan[3] underground detectors have detected a flux of high-energy muons ($E_\mu \lesssim 1$ TeV) which is two orders of magnitude higher than that expected from electromagnetic showers; third, there is no absorption of γ rays with $E_\gamma \cong 2\times10^{15}$ eV by the background-radiation photons, which should be described by a factor $k > 5$ at a distance $r > 13$ kpc from the source.

It can be shown that the observations rule out two other known neutral particles: neutrons and neutrinos. The qualitative suggestion was made in Ref. 4 (and also in Ref. 3) that the photino might solve all three of these difficulties. In the present letter we report quantitative calculations on this possibility.

2. Let us discuss very briefly the elementary processes by which photinos are produced and the important restrictions on the masses of the photino ($\tilde{\gamma}$), the gluino ($\tilde{g}$), and the quarkino ($\tilde{q}$). Photinos are produced in the source in *pp* scattering through the production of gluinos ($g + g \to \tilde{g} + \tilde{g}, q + \bar{q} \to \tilde{g} + \tilde{g}, g + q \to \tilde{g} + \tilde{q}$), followed by their decay $\tilde{g} \to \tilde{\gamma} + q + \bar{q}$. Large cross sections for the production of gluinos in *pp* scattering are possible only for a light gluino, $m_{\tilde{g}} \lesssim 10$ GeV. The experimental limitation on the gluino mass is a subject of some debate (see, e.g., Refs. 5 and 6 and the bibliographies there). The limitations on the masses of the photino, quarkino, and the electrino are[7] $m_{\tilde{\gamma}} > 0.5$ GeV and $m_{\tilde{q}}, m_{\tilde{e}} \gtrsim 20$ GeV.

3. As the model of Cygnus X-3, which is the best choice from the standpoint of the production of high-energy photinos, we consider a version of the model proposed in Ref. 8 for a hidden neutrino source (Fig. 1). The massive component ($M \sim 10M_\odot$), which fills its own Roche cavity, forms a binary system with an active pulsar that emits a beam of accelerated protons in the direction toward the observer. The gluinos are produced in the Roche cavity of the massive component, whose thickness $x \sim pR$ is significantly greater than the radiation length $x_{\rm rad} \sim 40$–60 g/cm^2, so that no γ emis-

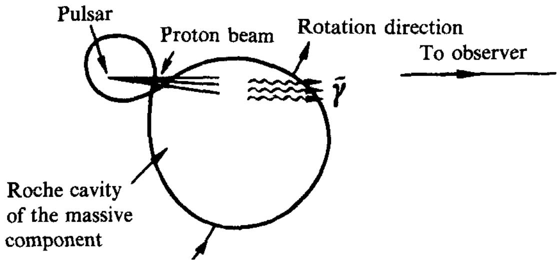

FIG. 1. Diagram illustrating the model of Cygnus X-3.

sion escapes outward. The number of protons of kinetic energy E which are emitted by the pulsar per 1 s in the form of a beam bounded by a solid angle Ω is

$$\dot{N}_p(E)dE=(\gamma-1)\gamma(E/E_0+1)^{-(\gamma+1)}(L_p/E_0)dE/E_0\,, \tag{1}$$

where γ is the index of the integral spectrum, E_0 is the normalization energy, and L_p is the luminosity of the pulsar in accelerated protons. Below we will use[1] $\gamma=1.1$ and $E_0=1$ GeV, and we will express all the energies and L_p in units of GeV and GeV/c. For the flux of photinos emitted we easily find, by analogy with neutrino production,[9]

$$F_{\tilde{\gamma}}(E)=(\tau_{\tilde{\gamma}}/T)\left[(\gamma-1)\gamma/(1-\alpha^{\gamma})\right]\varphi_{\tilde{\gamma}}(E)L_pE^{-(\gamma+1)}\,, \tag{2}$$

where $\tau_{\tilde{\gamma}}$ is the length of the photino pulse, $T=4.8$ h is the period of the source, $\alpha\approx0.5$ is the fraction of the energy retained by the proton in one inelastic pp collision, and $\varphi_{\tilde{\gamma}}(E)$ is the photino yield, given by

$$\varphi_{\tilde{\gamma}}(E)=\sum_{i=1}^{3}\chi_i\int_0^1 dy\,y^{\gamma}W(y)\int_0^1 dx\,x^{\gamma}\sigma_{in}^{-1}d\sigma_i(E/xy,x)/dx. \tag{3}$$

Here χ_i is the number of gluinos emitted in each of the three processes, $x=E_{\tilde{g}}/E_p$, $y=E_{\tilde{\gamma}}/E_{\tilde{g}}$, $W(y)=(5/3)-3y^2+(4/3)y^3$ is the probability for the production of a photino with an energy $yE_{\tilde{g}}$ during the decay of a gluino with an energy $E_{\tilde{g}}$ in the laboratory frame, and $\sigma_{\text{in}}\approx40$ mb is the cross section for inelastic pp scattering. To calculate $d\sigma_i(E_p,x)/dx$ we use deep inelastic production of gluinos with Duke-Owens and Gribov-Levin-Ryskin structure functions. The photino yields are shown in Fig. 2. They are to be compared with the yields of γ rays and $\nu_\mu+\bar{\nu}_\mu$ neutrinos[9]: $\varphi_\gamma\approx\varphi_{\nu_\mu}+\varphi_{\bar{\nu}_\mu}\approx0.12$.

4. We turn now to the interaction of photinos with matter in the earth's atmosphere. We first consider the reaction $\tilde{\gamma}+N\rightarrow\tilde{\gamma}+$ hadrons, which results from the resonant quark process $\tilde{\gamma}+q\rightarrow\tilde{q}$. Figure 3 shows the cross section for this process, calculated for quarkino masses $\tilde{m}_q=25$, 40, and 100 GeV (curves a, b, and c, respectively). The curve of the cross section is universal here because of the choice of variables: $m_{\tilde{q}}^2\sigma$ and $s/m_{\tilde{q}}^2$ along the ordinate and abscissa, respectively.

Another clearly resonant process, $\tilde{\gamma}+e\rightarrow\tilde{e}\rightarrow\tilde{\gamma}+e$, occurs at the photino energy $E_0=m_{\tilde{e}}^2/2m_e=1.6\times10^6(m_{\tilde{e}}/40\text{ GeV})^2$. It is analogous to the process

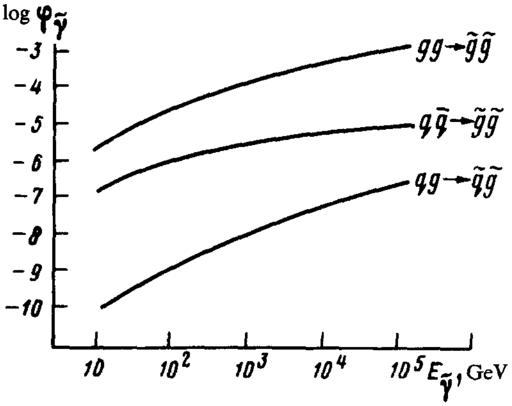

FIG. 2. Photino yield in pp scattering for $m_{\tilde g} = 3$ GeV and the reactions $g + g \to \tilde g + \tilde g$, $q + \bar q \to \tilde g + \tilde g$ and $g + q \to \tilde g + \tilde q$.

$\tilde\nu_e + e^- \to W^- \to \mu^- + \bar\nu_\mu$. Its cross section is of Breit-Wigner form:

$$\sigma(E_c) = \pi\Gamma^2/[(E_c - m_{\tilde e})^2 + \Gamma^2/4]m_{\tilde e}^2, \tag{4}$$

where $\Gamma = \alpha_{em}(m_{\tilde e}^2)m_{\tilde e}/2$ is the width of the decay $\tilde e \to \tilde\gamma + e$, and $\alpha_{em}(m_{\tilde e}^2) \approx 1/128$ is the electromagnetic constant with $Q^2 \sim m_{\tilde e}^2$. We find the number of resonant events as the photino flux passes through a thickness of the atmosphere with $N_e = \int n_e(r)dr$: electrons:

$$j_{res} = N_e \int j_{\tilde\gamma}(E)\,\sigma(E)\,dE. \tag{5}$$

Substituting (4) into (5), and using $E_c^2 = 2Em_e$, $E_0 = m_{\tilde e}^2/2m_e$ and $E_0 j_{\tilde\gamma}(E_0) = \gamma j_{\tilde\gamma}(>E_0)$ (which holds for a power spectrum), we find

$$j_{res} = N_e \sigma_{eff} \gamma j_{\tilde\gamma}(>E_0), \tag{6}$$

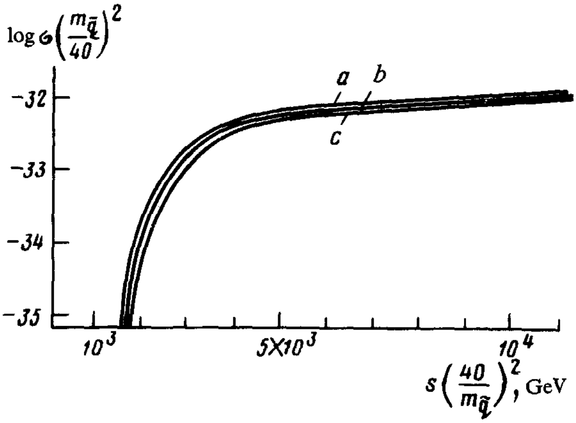

FIG. 3. Cross section for the reaction $\tilde\gamma + N \to \tilde\gamma + X$ calculated for three quarkino masses: a (upper curve)—25 GeV; b (middle-curve)—40 GeV; c (lower curve)—100 GeV. The quantities plotted along the axes are $s/m_{\tilde q}^2$ and $m_{\tilde q}^2\sigma$.

where $\sigma_{\text{eff}} = 2\pi^2\alpha_{em}/m_{\tilde{e}}^2 = 3.7\times10^{-32}\,(40\text{ GeV}/m_{\tilde{e}})^2\text{ cm}^2$. Formally, Eq. (6) means that each photino with an energy above the resonant energy interacts with an electron with a cross section $\sigma_{\text{eff}} \sim 4\times10^{-32}\text{ cm}^2$, although the actual physics of the phenomenon is of course different: All resonant events are caused by an interaction of photinos with energies in the interval $E_0 \pm \Delta E/2$, where $\Delta E \sim (m_{\tilde{e}}/m_e)\Gamma$. In (6), these events are "expanded" in all photinos with $E \geqslant E_0$. Since the condition $\sigma_{\text{eff}} > \sigma_{\tilde{\gamma}N}$ holds, the reaction $\tilde{\gamma} + e \to \tilde{e} \to \tilde{\gamma} + e$ is predominant in the generation of showers at $E \gtrsim E_0$. This reaction, which leads to purely electromagnetic showers, is "undesirable" from the standpoint of the muon component. It can be suppressed by assuming that $m_{\tilde{e}} > m_{\tilde{q}}$.

5. Let us discuss the observed effects.

The muon component of extensive air showers at sea level[1] can be explained in a natural way on the basis of the nuclear nature of the shower initiated by a photino ($\tilde{\gamma} + N \to \tilde{\gamma} +$ hadrons).

Photinos are also more efficient than photons in producing the high-energy muons ($E_\mu \gtrsim 1$ TeV) which are observed in underground experiments. The reason is that photinos with $E > 10^{15}$ eV interact primarily with the quark sea, where 1/3 of all quarks are s and $\bar{s}$ quarks. As a result, the cross section for the reaction $\tilde{\gamma} + N \to \tilde{\gamma} + K^{\pm} + X$ would be on the order of 1/2 of the cross section for the reaction $\tilde{\gamma} + N \to \tilde{\gamma} + \pi^{\pm} + X$. The production of muons with $E_\mu \gtrsim 1$ TeV in the atmosphere is more efficient through the decays of $K^{\pm}$ mesons than through the decays of $\pi^{\pm}$ mesons, since the latter do have time to decay over a nuclear range. Nevertheless, our calculations show that, either for interactions in the atmosphere or for interactions underground, photinos cannot explain the flux of muons with $E_\mu \gtrsim 1$ TeV observed in underground experiments.

The luminosity L_p which would be required in order to explain the flux of extensive air showers[1] on the basis of photinos is excessively large. Working from (2) with $r = 13$ kpc, the observed flux density[1a] $j(>2\times10^{15}\text{ eV}) = 7.4\times10^{-14}\text{ cm}^{-2}\cdot\text{s}^{-1}$, and $\tau_{\tilde{\gamma}}/T \approx 0.1$, we find that, even for a collimated proton beam, limited by a solid angle $\Omega = 0.01$, the luminosity L_p would have to be 2×10^{44} erg/s.

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[1] M. Samorsky and W. Stamm, Astrophys. J. Lett. **268**, 17 (1983); J. Lloyd-Evans *et al.*, Nature **305**, 784 (1983); C. Morello *et al.*, in: Proceedings of the Eighteenth International Cosmic Ray Conference, Bangalore, Vol. 1, 1983, p. 784; V. V. Alexeenko *et al.*, in: Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, Vol. 1, 1985, p. 91; A. Lambert *et al.*, in: Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, Vol. 1, 1985, p. 71; C. L. Bhat *et al.*, in: Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, Vol. 1, 1985, p. 83; P. R. Blake *et al.*, in: Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, Vol. 1, 1985, p. 66; T. Kifune, in: Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, Vol. 1, 1985, p. 67; R. M. Baltrusaitis *et al.*, in: Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, Vol. 1, 1985, p. 234; For a review of earlier studies of Cygnus X-3 see B. M. Vladimirskiĭ *et al.*, Usp. Fiz. Nauk **145**, 255 (1985) [Sov. Phys. Usp. **28**, 153 (1985)].

[2] J. Battisoni *et al.*, Phys. Lett. B, 1985 (to be published).

[3] M. L. Marshak *et al.*, Phys. Rev. Lett. **54**, 2079 (1985).

[4] V. J. Stenger, Nature, 1985 (to be published).

[5] J. Ellis and H. Kowalski, CERN Preprint TH-4126, 1985.

[6] A. De Rujula and R. Petronzio, CERN Preprint TH-4070, 1984.

[7] J. Ellis *et al.*, Nucl. Phys. **B238**, 453 (1984).
[8] V. S. Berezinsky, in: Proceedings of the 1979 DUMAND Workshop (ed. J. Learned), 1979, p. 245.
[9] V. S. Berezinskiĭ *et al.*, Astrofizika kosmicheskikh lucheĭ (Astrophysics of Cosmic Rays), Nauka, Moscow, 1984.

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