Astroparticle Physics 71 (2015) 1–20

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

Review

Could a plasma in quasi-thermal equilibrium be associated to the “orphan” TeV flares?

N. Fraija [1]

Instituto de Astronomía, Universidad Nacional Autónoma de México, Circuito Exterior, C.U., A. Postal 70-264, 04510 México D.F., Mexico

ARTICLE INFO

Article history:
Received 25 March 2015
Revised 14 April 2015
Accepted 27 April 2015
Available online 14 May 2015

Keywords:
Gamma rays: general
Galaxies: BL Lacertae objects individual (Mrk 421)
Galaxies: BL Lacertae objects individual (1ES 1959+650)
Physical data and processes: acceleration of particles
Physical data and processes: radiation mechanism: nonthermal
Neutrino oscillation

ABSTRACT

TeV γ-ray detections in flaring states without activity in X-rays from blazars have attracted much attention due to the irregularity of these “orphan” flares. Although the synchrotron self-Compton model has been very successful in explaining the spectral energy distribution and spectral variability of these sources, it has not been able to describe these atypical flaring events. On the other hand, an electron–positron pair plasma at the base of the AGN jet was proposed as the mechanism of bulk acceleration of relativistic outflows. This plasma in quasi-thermal equilibrium called Wein fireball emits radiation at MeV-peak energies serving as target of accelerated protons. In this work we describe the “orphan” TeV flares presented in blazars 1ES 1959+650 and Mrk 421 assuming geometrical considerations in the jet and evoking the interactions of Fermi-accelerated protons and MeV-peak target photons coming from the Wein fireball. After describing successfully these “orphan” TeV flares, we correlate the TeV γ-ray, neutrino and UHECR fluxes through $p\gamma$ interactions and calculate the number of high-energy neutrinos and UHECRs expected in IceCube/AMANDA and TA experiment, respectively. In addition, thermal MeV neutrinos produced mainly through electron–positron annihilation at the Wein fireball will be able to propagate through it. By considering two- (solar, atmospheric and accelerator parameters) and three-neutrino mixing, we study the resonant oscillations and estimate the neutrino flavor ratios as well as the number of thermal neutrinos expected on Earth.

Contents

E-mail address: nifraija@astro.unam.mx
[1] Luc Binette-Fundación UNAM Fellow.

http://dx.doi.org/10.1016/j.astropartphys.2015.04.007
0927-6505/

1. Introduction

Flares observed in very-high-energy (VHE) γ-rays with absence of high activity in X-rays, are very difficult to reconcile with the standard synchrotron self-Compton (SSC) although it has been very successful in explaining the spectral energy distribution (SED) of blazars [1–3]. Although most of the flaring activities occur almost simultaneously with TeV γ-ray and X-ray fluxes, observations of 1ES 1959+650 [4–6] and Mrk 421 [7,8] have exhibited VHE γ-ray flares without their counterparts in X-rays, called "orphan" flares.

Leptonic and hadronic models have been developed to explain orphan flares. A leptonic model based on geometrical considerations about the jet has been explored to reconcile the SSC model [9] whereas hadronic models where accelerated protons interact with both external photons generated by electron synchrotron radiation [10] and SSC photons at the low-energy tail [11] have been performed to explain this anomalous behavior in these blazars. Based on these models HE neutrino emission has been studied by Reimer et al. [12] and Halzen and Hooper [13]. In particular for the blazar 1ES 1959+650, Halzen and Hooper [13] based on proton–proton (pp) and proton–photon ($p\gamma$) interactions estimated the number of events expected in Antarctic Muon And Neutrino Detector Array (AMANDA). They found that the neutrino rates were 1.8 (10^{-3}) events for pp ($p\gamma$) interactions.

It has been widely suggested that relativistic jets of active galactic nuclei (AGN) contain electron–positron pairs produced from accretion disks [14–16]. Also electron–positron pair plasma has been proposed as a mechanism of bulk acceleration of relativistic outflows. In gamma ray burst (GRB) jets, this plasma "fireball" formed inside the initial scale $\sim 10^7$ cm is made of photons, a small amount of baryons and $e^{\pm}$ pairs in thermal equilibrium at some MeV [17]. However, in AGN jets the fireball cannot be formed because the characteristic size is too large ($3r_g \sim 10^{14}$ cm) in comparison with GRB jets. Some authors found that if the pair plasma is expected to be optically thin to absorption but thick to scattering, the "Wein fireball" could exist, even though for the size and luminosity of AGNs [18–20]. Afterward, simulations with protons inside this plasma were performed by Asano and Takahara [21,22].

At the initial stage of the Wein fireball, thermal neutrinos will be mainly created by electron–positron annihilation ($e^+ + e^- \to Z \to \nu_j + \overline{\nu}_j$). By considering a small amount of baryons, neutrinos could also be generated by processes of positron capture on neutrons ($e^+ + n \to p + \overline{\nu_e}$), electron capture on protons ($e^- + p \to n + \nu_e$) and nucleon-nucleon bremsstrahlung ($NN \to NN + \nu_j + \overline{\nu}_j$) for $j = e, \nu, \tau$. Taking into account that the temperature of Wein fireball is relativistic [19,20], then neutrinos of 1–5 MeV can be produced and fractions of them will be able to go through this plasma. As known, the neutrino properties are modified when they propagate through a thermal medium, and although neutrino cannot couple directly to the magnetic field, its effect can be experimented through coupling to charged particles in the medium [23]. The resonance conversion of neutrino from one flavor to another due to the medium effect, known as Mikheyev–Smirnov–Wolfenstein effect [24], has been widely studied in the GRB fireball [25–27].

Telescope array (TA) experiment reported the arrival of 72 ultra-high-energy cosmic rays (UHECRs) above 57 EeV with a statistical significance of 5.1σ. These events correspond to the period from 2008 May 11 to 2013 May 4. Assuming the error reported by TA experiment in the reconstructed directions, some UHECRs might be associated to the position of Mrk 421 [28]. In addition, IceCube collaboration reported the detection of 37 extraterrestrial neutrinos at 4σ level above 30 TeV [29,30], although none of them located in the direction of neither 1ES 1959+650 nor Mrk 421, as shown in Fig. 1.

Because TeV γ-ray "orphan" flares are very difficult to reconcile with SSC model, in this work we introduce a hadronic model by means of $p\gamma$ interactions to explain these atypical TeV flares registered in blazars 1ES 1959+650 and Mrk 421. In this model, we consider some geometrical assumptions of the jet and the interactions between the MeV-peak photons coming from the Wein fireball and relativistic protons accelerated at the emitting region. Then, we correlate the TeV γ-ray, neutrino and UHECR fluxes to calculate the number of HE neutrino and UHECR events. In addition, we study the resonance oscillations of thermal MeV neutrinos. The paper is arranged as follows. In Section 2 we show the dynamic model of the radiation coming from Wein fireball and its interactions with the protons accelerated at the emitting region. In Section 3 we study the emission, production and oscillation of neutrinos. In Section 4 we discuss the mechanisms for accelerating UHECRs and also estimate the number of these events expected in the TA experiment, supposing that the proton spectrum is extended up to energies greater than 57 EeV. In Section 5 we describe the TeV orphan flares of the blazars 1ES 1959+650 and Mrk 421 and give a discussion on our results; a brief summary is given in Section 6. We hereafter use primes (unprimes) to define the quantities in a comoving (observer) frame, natural units ($c = \hbar = k = 1$) and redshifts $z \simeq 0$.

2. Orphan TeV γ-ray emission

Different hadronic models have been considered to explain TeV γ-ray observations presented in blazars [31–34]. In those models, SEDs are described in terms of co-accelerated electrons and protons at the emitting region. In this hadronic model, we describe the TeV γ-ray emission through π^0 decay products generated in the interactions of accelerated protons and seed photons coming from the Wein fireball, as shown in Fig. 2.

2.1. MeV radiation from the Wein fireball

The Wein fireball connects the base of the jet with the black hole (BH). We assume that at the initial state, it is formed by $e^{\pm}$ pairs with photons inside the initial scale $r_o = 2r_g = 4GM$, being G the gravitational constant and M the BH mass. The initial temperature can be defined through microscopic processes at the base of the jet (Compton scattering, $\gamma\gamma$ pair production, etc). At the first state, photons inside the Wein fireball are at relativistic temperature. The internal energy starts to be converted into kinetic energy and the Wein fireball begins to expand. As a result of this expansion, temperature decreases and bulk Lorentz factor increases at the first state. The initial optical depth is [20,19]

$$\tau_o \simeq \frac{n_{e,o}\sigma_T r_o}{\Gamma_{W,o}}, \tag{1}$$