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A single zone synchrotron model for flares of PKS1510-089

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ABSTRACT

PKS 1510-089 is one of the most variable blazars. Very high energy gamma ray emission from this source was observed by H.E.S.S. during March-April 2009 and by MAGIC from February 3 to April 3, 2012 quasi-simultaneously with multi-wavelength flares. The spectral energy distributions of these flares have been modeled earlier with the external Compton mechanism which depends on our knowledge of the densities of the seed photons in the broad line region, the dusty infrared torus or a hypothetical slow sheath surrounding the jet around the radio core. Here we show that to explain the multi-wavelength data with synchrotron emission of electrons and protons the jet power should be of the order of 10^{48} ergs/s.

1. Introduction

With the successful operation of the high energy gamma ray detectors it has become possible to study blazar flares even at very high energies. Blazars have relativistic jets directed toward us where the radiation losses from the relativistic electrons and protons result in the emission of photons of radio to gamma ray frequencies.

They are powerful sources of GeV-TeV gamma rays. Their spectral attenuations at very high energy with cosmological distances are widely used to study the absorption of high energy gamma rays by the extragalactic background light (EBL) [1].

Their spectral energy distributions (SEDs) have two broad peaks. The peak at low frequency originates from synchrotron radiations of accelerated electrons in the relativistic jet and the peak at higher frequency from the inverse Compton scattering of these electrons by the seed photons in the jet, and the external regions including the disc torus, the broad line region (BLR).

The high energy hump may also originate from synchrotron emission of accelerated protons in the jet and hadronic interactions [2,3]. Hadronic interactions could be between accelerated protons and cold matter or low energy photons.

Flat Spectrum Radio Quasars (FSRQs) and BL Lacs are two different classes of blazars having different spectral features. FSRQs have bright optical and UV emission lines [4], also they are more luminous in high energy photons than BL Lacs. External Compton (EC) mechanism successfully describes the high energy emission from FSRQs in most cases while synchrotron self Compton (SSC) emission is the most popular scenario for BL Lacs.

PKS 1510-089, PKS 1222+21, and 3C 279 are the three FSRQs observed in gamma rays of energy more than 100 GeV. The flares from 3C 279 have been modeled earlier with the synchrotron emission from accelerated electrons and protons, also with the two zone SSC model [5].

PKS 1510-089 is a FSRQ located at a redshift of 0.361 with highly polarised radio and optical emission. Although many FSRQs have been found to have a spectral break in the frequency range of a few GeV [6], the SED of PKS 1510-089 shows no such distinctive feature. In fact the transition from the high energy (HE:100 MeV to 100 GeV) to VHE range is quite smooth for the observed data.

It has a black hole of mass 5.6×10^8 times the mass of sun estimated from its accretion disc temperature and UV flux [7]. Fermi LAT and AGILE detectors have detected highly variable gamma ray emission from it. Detection of gamma rays of energy upto 300–400 GeV has been reported by the H.E.S.S. collaboration [8] during March–April, 2009 and the MAGIC collaboration [9] from February 3 to April 3, 2012.

The quasi-simultaneous data from radio, optical, X-ray and gamma ray telescopes have been combined and modeled with EC mechanism in [10]. They showed that the H.E.S.S. data given in [11] could be included in their single zone model if EC emission happens due to the seed photons in the BLR and the dusty torus of PKS 1510-089. They also included the effect of the internal absorption of the gamma rays due to pair production with the photons in the blazar environment. Their model is primarily based on the assumption that the emission region is located near the central core i.e., the near dissipation zone scenario [6]. Moreover, the absorption of the gamma rays by the EBL further attenuates the gamma ray spectrum before detection.

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However according to the findings of [12] it is possible that the emission region is located at large distances (tens of parsecs) from the blazar core. This would mean that the BLR cloud and the IR dusty torus can no longer act as possible sources of seed photons. In order to overcome this complication it has been hypothesized that the jet may have components moving with different relative velocities which provide the necessary seed photons for IC scattering. The authors of [9] have considered both the far and near dissipation zone scenarios while modeling the SED obtained from observations. For the near dissipation zone scenario the IR torus was considered as the source of seed photons. Whereas for the far dissipation zone scenario they have considered a slow moving sheath enveloping the faster moving spine of the jet as the source of seed photons.

PKS 1510-089 was detected in flaring states by the HESS and MAGIC telescopes in 2009 and 2012 respectively. In the present work we have used a single zone lepto-hadronic model to explain the multi-wavelength data during these flares. The lower energy peak is attributed to electron synchrotron mechanism whereas we consider the proton synchrotron mechanism for explaining the higher energy bump. Unlike the previous models we do not need to consider external sources of photons to explain the observed spectra. The following sections describe our work in detail.

2. Modeling the SED

The multi-wavelength data presented in [10] and [9] [Observation timeline :– March–April(2009) & February–April(2012) respectively] have been modeled in our work. PKS 1510-089 was active in the VHE regime during these periods.

We have used the code developed in [13] to generate the synchrotron spectra from relativistic electrons and protons in the jet of PKS 1510-089. To model the higher energy bump in the SED, we consider a population of relativistic protons in this energy range $10^{15} < E^{proton} < 10^{20}$ eV. The relativistic protons are losing energy by synchrotron emission at a much slower rate compared to the relativistic electrons. Diffusion losses are assumed to be negligible for the relativistic protons in our model. Also, the energy loss of the very high energy protons due to $p\gamma$ interactions is found to be insignificant compared to synchrotron losses for the parameter values used in our study. Their injected spectrum remains essentially unchanged as their cooling time scales are much larger than the time scale of the flares in our study. The injected spectrum $(\frac{dQ(E^{proton})}{dE^{proton}})$ of protons is assumed to follow a broken power law with spectral indices p_1 and p_2 below and above the break energy respectively. In our model $p_1 \sim 2$ and the values of p_2, the break energy are adjusted to fit the observed SED. Due to inefficient cooling of protons we need very high luminosity in protons to explain the high energy data in the SEDs of flares with proton synchrotron emission.

In our model the most important cooling mechanism for relativistic electrons is synchrotron emission. Their injected spectrum is assumed to be a simple power law with $p_1 \sim 2$. The emission region is assumed to be a spherical blob of radius R moving with relativistic speed. The break energy in the propagated spectrum of electrons is calculated using the following condition

$$t_{synch}^{electron} \simeq \frac{7.75 \times 10^8}{B^2 \times \gamma_{break}^{electron}} = \frac{R}{c} \tag{1}$$

where $\gamma_{break}^{electron} = \frac{E_{break}^{electron}}{m_{electron}c^2}$. Beyond the break energy the propagated spectrum of electrons steepens by a factor of $1/E_{electron}$ due to synchrotron cooling. We note that the light crossing time (R/c) is comparable to the time scale of the flares measured in the jet frame. The above condition ensures that below the cooling break energy the synchrotron photons from the entire spherical region of radius R contribute to the observed flux.

The radius of the spherical emission region (R in cm) is larger than the Larmor radius of the highest energy protons ($E_{\max}^{proton}$ in eV) in our model. Eq. (2) represents this condition below

$$B \geqslant 30 \frac{E_{max}^{proton}}{10^{19}} \frac{10^{15}}{R} \quad \text{in Gauss.} \tag{2}$$

The ambient magnetic field (B) is constrained by Eqs. (1) and (2). We have chosen two different values for B, 0.42 G & 0.62 G while modeling the observed SEDs.

The parameters such as redshift (z = 0.361 for PKS 1510-089), bulk Lorentz factor(Γ), viewing angle(θ_{obs}) are dependent on direct observations. Although we cannot measure Γ and θ_{obs} in the same way we can measure the redshift, the observed apparent velocity ($\sim$20c–45c) of the relativistic jet [14] does indicate a very small viewing angle (1.4°–3°) [12,15–17] which in turn constrains the value of the Lorentz factor according to the relation $\Gamma \simeq \frac{1}{\theta_{obs}}$. Due to the extremely high apparent superluminal motion displayed by the jet the value of the Doppler factor ($\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$) should also be very high. We have selected $\delta = 20$ & 36 by appropriately adjusting the values of θ_{obs} & Γ while fitting the observed data. The code from [13] used in our work also requires the energy density of the particles in the jet frame $u'_{particle}$ as a input parameter. As the jet power is directly proportional to the energy density of particles, a lower value of this parameter is always preferred.

The radius of the emission region is generally constrained by the flux variability of the source according to the relation $R \leq \frac{c\Delta t_{obs}\delta}{1+z}$ where Δt_{obs} is the observed variability timescale. As no significant variability was detected during the VHE emissions either by H.E.S.S. or MAGIC we cannot infer any strong upper limit on the radius. However in the HE γ-ray regime AGILE-GRID has registered 7 days and 14 days for two distinctive flares, Flare-I and Flare-II respectively in 2012 [9]. Also, the HE data shows variability in shorter time scale which may originate from fluctuations in magnetic field and particle density within a smaller region. For $\delta = 36$, the radius of the emission region for the AGILE-GRID observations should be 4.79×10^{17} and 9.58×10^{17} cms for Flare-I and II respectively. Similarly for $\delta = 20$ the estimates of R are found to be 2.66×10^{17} and 5.33×10^{17} cms respectively for Flare-I and Flare-II. The variability in the radio frequency range was also in the timescale of weeks during that observing period. Also during the observations in 2009 [10] two distinct flares were detected by *Fermi*-LAT within a duration of 42 days. It is important to mention in this context that the above relation is an approximate one and might lead to large errors while estimating the dimensions of the emitting region [18]. Thus considering all the factors discussed above we have assumed the value of R as 5.7×10^{17} cm for our emission region which is in agreement with the choice of R used by [10] & [9] previously while modeling the 2009 & 2012 observations respectively. Although this choice of R is not consistent with the hour scale variability during the γ-ray emission reported by *Fermi*-LAT ([19–21]) it must be noted that as the multiwavelength data reported during the two high activity states of PKS 1510-089 (2009 and 2012) are at best quasi-simultaneous in nature the SED represents an average emission state of the source. As a result of this the models presented in our paper and also in [10], [9] are not expected to account for the separately observed shorter timescale variabilities. According to [12], [22] & [23] the rapid flickering may be attributed to turbulence within the jet flow and it need not be absolutely essential that the volume of the emission region should have these rapid variabilities as a constraining factor. It may be possible that isolated regions with slightly different magnetic field signatures and particle populations with a different energy range and energy density exist within the larger emitting region and the