Implications of the VHE $\gamma$-Ray Detection of 3C279

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Abstract. We present simultaneous optical (BVRI) and X-ray (RXTE PCA) data on the quasar 3C279 from the day of the recent VHE detection by MAGIC and discuss the implications of the snapshot spectral energy distribution (SED) for leptonic jet models of blazars. A one-zone synchrotron-self-Compton origin of the SED up to VHE $\gamma$-rays can be ruled out. The VHE emission could, in principle, be interpreted as Compton upscattering of external radiation (e.g., from the broad-line regions) an unrealistically high Doppler factor of $\Gamma \sim 140$. In addition, such a model fails to reproduce the observed X-ray flux. We therefore conclude that a simple one-zone, homogeneous leptonic jet model is not able to plausibly reproduce the SED of 3C279 including the recently detected VHE $\gamma$-ray emission. This as well as the lag of correlated variability in the optical with the VHE $\gamma$-ray emission suggests a multi-zone model in which the optical emission is produced in a different region than the VHE $\gamma$-ray emission. Alternatively, also a hadronic origin of the VHE $\gamma$-rays seems plausible.

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INTRODUCTION

The quasar 3C279 ($z = 0.538$) is one of the best-observed flat spectrum radio quasars, in part because of its prominent $\gamma$-ray flare shortly after the launch of the Compton Gamma-Ray Observatory (CGRO) in 1991. It was persistently detected by the Energetic Gamma-ray Experiment Telescope (EGRET) on board CGRO each time it was observed, even in its very low quiescent states, e.g., in the winter of 1992–1993, and is known to vary in $\gamma$-ray flux by roughly two orders of magnitude [13, 20].

A complete compilation and modeling of all available SEDs simultaneous with the 11 EGRET observing epochs has been presented in [11]. The modeling was done using the time-dependent leptonic synchrotron self-Compton (SSC) + External Compton (EC) model of [6, 7] and yielded quite satisfactory fits for all epochs. The results were consistent with other model fitting works [e.g., 2, 18, 15] concluding that the X-ray – soft $\gamma$-ray portion of the SED might be dominated by SSC emission, while the EGRET emission might require an additional, most likely external-Compton, component.

During a recent observing campaign by the Whole Earth Blazar Telescope (WEBT) collaboration [9] in the spring of 2006, intensive monitoring by the Major Atmospheric Gamma-Ray Imaging Cherenkov Telescope (MAGIC) yielded a positive detection at $>100$ GeV on February 23, 2006 [1]. This makes 3C279 the first quasar and (as of August 2008) the most distant object detected in VHE $\gamma$-rays. In this paper, we discuss the implications of the simultaneous SED of 3C279, including optical (BVRI), X-ray (RXTE), and VHE $\gamma$-rays, for current standard blazar jet models.

Throughout this paper, we refer to $\alpha$ as the energy spectral index, $F_\nu \propto \nu^{-\alpha}$. A cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ is used. In this cosmology, and using the redshift of $z = 0.538$, the luminosity distance of 3C 279 is $d_L = 3.1$ Gpc.
OBSERVATIONAL RESULTS

3C 279 was observed in a WEBT campaign at radio, near-IR, optical frequencies, throughout the spring of 2006 [9]. The source was simultaneously monitored with 3 pointings per week with the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA), using detector PCU2 with typical exposure times of 2 ks for each pointing. We processed the data in the same manner as for 3C 120, described in [14], except with updated software and background model. Fig. 1 shows the radio, optical and X-ray light curves of 3C279 during spring 2006, along with the 2 – 10 keV spectral index [5]. The dashed vertical line marks the day of the MAGIC > 100 GeV γ-ray detection. While the source was overall in an extended optical high state \((R \sim 14.5)\), no extraordinary variability in any (BVRI) band was observed at the time of the MAGIC detection.

During most of December 2005 and January 2006, the X-ray flux of 3C279 was in a low state, near its historical minimum. Around Jan. 25, however, the source made a transition to a higher X-ray flux state with substantial variability in flux and spectral index on a characteristic time scale of \(\sim 10\) days. In the high state, there is a clear correlation between X-ray flux and spectral hardness, with the spectrum becoming harder as the flux increases. The VHE flare observed by MAGIC precedes an X-ray outburst with the highest X-ray flux measured since the major optical/X-ray outburst in 2001, by \(\sim 5 – 7\) days.

Fig. 2 compares several historical SEDs of 3C279 to the one measured on February 23, 2006, along with the MAGIC VHE detection and the attempts of leptonic fits to be discussed in the following section. The optical spectrum, while clearly in an elevated state, shows about the same, steep spectral index \(\alpha_{\text{opt}} \sim 1.7\) as during lower optical flux states, indicating an underlying nonthermal electron spectral index of \(p = 4.4\).

For the purpose of a quantitative analysis, the following observables can be estimated from the February 23, 2006, SED: The synchrotron peak might be located in the infrared regime, around \(v_{\text{cy}} \sim 5 \times 10^{12}\) Hz, corresponding to a dimensionless photon energy \(\epsilon_{\text{cy}} \equiv \hbar v_{\text{cy}}/(m_e c^2) \sim 4 \times 10^{-7}\). The poorly constrained synchrotron peak flux might be of the order of \(F_{\gamma} \sim 10^{13}\) Jy Hz. If a one-zone leptonic jet model (as discussed in the following section) applies, the VHE spectrum is expected to have a similarly steep slope as the optical (synchrotron) emission. Therefore, in order not to predict a GeV γ-ray flux greatly in excess of any archival EGRET flux, it is reasonable to assume a γ-ray peak at \(v_{\gamma} \sim 10^{23}\) Hz, corresponding to \(\epsilon_{\gamma} \sim 10^5\). The γ-ray peak flux is then \(F_{\gamma} = 5 \times 10^{13}\) Jy Hz. From the spectral upturn in the UV in the P2-spectrum in Fig. 2, we can estimate a thermal (external) photon source with a luminosity of \(L_D \sim 2 \times 10^{45}\) erg s\(^{-1}\), peaking at \(v_D \sim 10^{15}\) Hz \((\epsilon_D \sim 10^{-5})\).

IMPLICATIONS FOR LEPTONIC JET MODELS

We consider a scenario in which a nonthermal population of ultrarelativistic electrons produces, at the same time, the synchrotron emission from radio through UV and the X-ray - γ-ray emission via Compton scattering of soft photons off the relativistic electrons. In general, we will assume that electrons are accelerated into a power-law distribution in electron energy, \(Q(\gamma) = Q_0 \gamma^{-\alpha}\) for \(\gamma_1 \leq \gamma \leq \gamma_2\). The interplay between radiative cooling and escape leads to the development of a spectral break in the electron spectrum at a Lorentz factor \(\gamma_0\), where the radiative cooling time scale equals the escape time scale, \(t_{\text{esc}} \equiv \eta_{\text{esc}} R / c\). Given the steep spectral index of the optical spectrum, implying \(p = 4.4\) in the electron energy range synchrotron-radiating in the optical regime, a characteristic cooling break from \(p = 3.4\) to \(p = 4.4\), as expected in the slow cooling regime, would not produce a peak in the \(F_{\gamma}\) spectrum at the characteristic synchrotron frequency corresponding to \(\gamma_0\). Therefore, it is likely that the injected electron distribution has a high low-energy cutoff at \(\gamma_1 > \gamma_0\). In this case, particles at energies \(\gamma < \gamma_1\) result only from radiative cooling from...
higher energies, resulting in an electron spectrum with a spectral index $p = 2$ in the range $\gamma_s < \gamma < \gamma_1$, while above $\gamma_1$, we have $p = q + 1$, as in the slow cooling case.

### SSC model

Given the synchrotron origin of the low-frequency peak at $\nu_{sy} \sim 4 \times 10^{-7}$ and the SSC origin of the $\gamma$-ray peak at $\nu_\gamma \sim 10^5$, the Lorentz factor of electrons $\gamma_{p}$ radiating at the synchrotron and SSC peaks, can be estimated from

$$\gamma_p = \sqrt{\frac{\nu_{\gamma}}{\nu_{sy}}} \approx 1.6 \times 10^5. \quad (1)$$

At the same time, the synchrotron peak frequency is given by

$$\nu_{sy} = 4.2 \times 10^6 \gamma_{p}^2 B_G D/(1 + z) \text{ Hz} \quad (2)$$

where $B_G$ is the (co-moving) magnetic field in Gauss, and $D \equiv 10D_L = (1 - \beta \cos \theta_{\text{obs}})^{-1}$ is the Doppler enhancement factor. This yields an estimate of the magnetic field and the Doppler factor of

$$B_G D_1 \sim 7 \times 10^{-5}. \quad (3)$$

This indicates that such a scenario would imply unrealistically low magnetic fields compared to standard values of $\sim 1$ G found from SED modeling of 3C279 in other states, as well as other blazar-type quasars. We can therefore rule out a one-zone SSC origin of the VHE emission of 3C279.

### External Compton

Our external-Compton scenario is based on the assumption that photons from an external, quasi-isotropic radiation field with dimensionless photon energy $\epsilon_s$ is Compton-upscattered to the observed $\gamma$-ray photon energies. Such photons can be upscattered effectively in the Thomson regime at most up to energies $\epsilon_\gamma = 1/\epsilon_s$. This indicates that a photon field with a characteristic photon energy of the accretion disk field at $\epsilon_D \sim 10^{-5}$ can effectively serve as the seed photon field for upscattering to the observed $> 100$ GeV $\gamma$-rays. We assume that a fraction $\tau_{BLR} \equiv 10^{-4} \tau_{-1}$ of the accretion disk radiation is reprocessed in the broad line region, which is located at an average distance $R_{BLR} \equiv 0.1 R_{BLR,-1}$ pc from the central engine. HST near-UV spectroscopy [16] indicates that the total luminosity of the BLR in 3C279 is $L_{BLR} \sim \tau_{BLR} L_D \sim 2 \times 10^{44} \text{ erg/s}$, motivating the above scaling in terms of $\tau_{-1}$. In the co-moving frame, the external photons will thus have a characteristic energy of $\epsilon'_{s} = \Gamma \epsilon_s$. In addition to Eq. (2), we now have an independent estimate for $\gamma_s$, namely

$$\gamma_s = \sqrt{\frac{\epsilon_s}{\Gamma^2 \epsilon_D}} \sim 10^4 \Gamma_{-1}. \quad (4)$$

We can use Eq. (2) to obtain an estimate for the magnetic field:

$$B_G = 1.8 \times 10^{-2} \Gamma_1^2 D_1^{-1}. \quad (5)$$

The energy density of external photons in the co-moving frame can be expressed as

$$u'_{\text{ext}} \sim \frac{L_D \tau_{BLR} \Gamma^2}{4\pi R^2_{BLR} c}. \quad (6)$$

From the $\gamma$-ray dominance, $L_\gamma/L_{sy} \sim u'_{\text{ext}}/u_B \sim 5$, we can then obtain an independent estimate of the magnetic field of

$$B_G = 1.0 \epsilon_\gamma^{1/2} \Gamma_1 R_{BLR,-1}. \quad (7)$$

Combining the magnetic field estimates (5) and (7), we find

$$R_{BLR,-1} = 57 \epsilon_\gamma^{1/2} \Gamma_{-1} \quad (8)$$

which is in drastic contrast to the estimate of [16] of $R_{BLR} \sim 3 \times 10^{-2}$ pc.

Considering the peak level of the synchrotron flux, we can use Eq. (8) of [8] to relate the magnetic field in the emission region with the equipartition fraction $\epsilon_B \equiv u_B/u'_s$, i.e., the ratio of co-moving energy densities in the magnetic field and the nonrelativistic electron population:

$$B_{\epsilon B} = 1.25 D_1^{-1} \left( \frac{d^_{\gamma \gamma} f_2^{10} \epsilon_B^3}{[1 + \delta^4 \epsilon_{sy,-6} R_{16}^0 (p - 2)]} \right)^{1/7}. \quad (9)$$

Setting this equal to the magnetic-field estimate (5) yields

$$\epsilon_B = 9.7 \times 10^{-9} R_{16}^3 \Gamma_1. \quad (10)$$

Consequently, if we choose a conventional value of the Lorentz factor $\Gamma \sim 15$, we find an uncomfortably low magnetic field of $B \sim 0.03$ G, corresponding to $\epsilon_B \sim 1.7 \times 10^{-7} R_{16}^0$, i.e., a far sub-equipartition magnetic field. Such a situation would make jet confinement very problematic, and is in contradiction with model results for 3C279 in other observing epochs and for other quasar-type blazars in general, where magnetic fields of typically $B \sim 1 – 5$ G are inferred, in approximate equipartition with the relativistic electron population.
Alternatively, forcing the system to attain approximate equipartition, would require us to assume an uncomfortably high Lorentz factor of $\Gamma \sim 140R^{3/2}$. This choice of a bulk Lorentz (and Doppler) factor would imply $B \sim 0.25$ G, and a low-energy cut-off of the injected electron population at $\gamma_{e} = \gamma_{p} \sim 710R_{140}^{3/2}$. Apart from the fact that this is an order of magnitude larger than bulk Lorentz factors inferred from superluminal motion, it would require an implausibly close alignment of the jet with our line of sight, $\theta_{\text{obs}} \sim 0.4^\circ$. We note that the magnetic-field estimate of Eq. (5) carries a proportionality $B \propto (\varepsilon_{*}/\varepsilon_{D})$. Since our choice of $\varepsilon_{*} \sim 10^{-5}$ is already close to the largest possible value to allow Thomson scattering to TeV $\gamma$-rays, the assumption of a different soft photon source (necessarily with a smaller $\varepsilon_{*}$) would worsen the problem of the unusually small inferred magnetic field.

It has been noted by several authors that the $\gamma\gamma$ absorption of VHE $\gamma$-ray photons by the radiation field of the BLR may present another problem for a model of VHE $\gamma$-ray emission inside the BLR of luminous quasars in general [e.g. 10, 17] and 3C279 in particular [12, 19]. In order to verify whether this is another severe problem for the parameters we inferred above, we have used the formalism developed in [4], where the time-dependent $\gamma\gamma$ absorption signatures of an accretion disk flare (reflected by BLR clouds) on VHE $\gamma$-ray emission were investigated. We have modified their approach to use a steady standard accretion-disk spectrum approximated by a spectral shape $F_{\gamma} \propto \varepsilon^{-1/3} e^{-\varepsilon_{D}/\varepsilon_{D}}$, where $\varepsilon_{D} = 10^{-5}$ is the dimensionless inner disk temperature, $\Theta_{D} = kT_{\text{disk}}/(mc^{2})$. Our results confirm the findings of [12]: With standard values of the BLR parameters, $\tau_{\text{BLR}} \sim 0.1, R_{\text{BLR}} \sim 0.2$ pc, as inferred by [16], VHE $\gamma$-rays produced within the BLR of 3C279 suffer severe $\gamma\gamma$ absorption by the same photon field that would serve as seed photon field for Compton scattering in a leptonic model. For the extreme parameters of $\Gamma \sim 140$, requiring $R_{\text{BLR}} \sim 5.7$ pc, $\tau_{\text{BLR}} \sim 0.1$, $\gamma\gamma$ absorption would hardly be a problem even out to multi-TeV $\gamma$-ray energies, if the $\gamma$-rays are produced close to the inner boundary of the BLR.

The red, solid curve in Fig. 2 shows a leptonic model calculation with parameters similar to the quasi-equipartition case outlined above. We used an equilibrium version of the time-dependent SSC + EC model of [3]. While the optical (synchrotron) and VHE $\gamma$-ray spectra can reasonably well be reproduced, it is obvious that the X-ray flux is grossly underproduced. This is a consequence of the required, rather large low-energy cutoff at $\gamma_{e} \sim 700$.

We therefore conclude that both the SSC and the external-Compton scenario for a one-zone, homogeneous jet model are unlikely to be the correct interpretation of the VHE $\gamma$-ray emission of 3C279.

As noted earlier, the VHE $\gamma$-ray flare was not accompanied by any remarkable optical variability. This may be another hint that in 3C279 the optical and $\gamma$-ray fluxes may be produced in separate emission regions. However, the calculation of the $\gamma\gamma$ opacity above indicates that even an inhomogeneous leptonic jet model would face severe problems in an external-Compton scenario. The dashed red curve in Fig. 2 indicates that an SSC model can successfully reproduce the X-ray – VHE $\gamma$-ray spectrum with reasonable parameters, but fails to reproduce the optical spectrum. This may indicate support for a two-zone leptonic model. This would require that the VHE $\gamma$-ray emission is produced far outside the BLR, possibly in an internal shock scenario. This is indicated both by the $\gamma\gamma$ opacity argument as well as the low required magnetic field for the SSC fit presented in Fig. 2.

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REFERENCES