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A synchrotron self-Compton scenario for the very high energy γ-ray emission of the intermediate BL Lacertae object W Comae *

Jin Zhang[1,2,3]

[1] National Astronomical Observatories/ Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, China; *jinzhang@ynao.ac.cn*

[2] College of Physics and Electronic Engineering, Guangxi Teachers Education University, Nanning 530001, China

[3] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract W Comae has significant variability in multi-wavelengthes, from radio to gamma-ray bands. A bright outburst in optical and X-ray bands was observed in 1998, and most recently, a strong TeV flare was detected by VERITAS in 2008. It is the first TeV intermediate-frequency-peaked BL Lacertae source. I find that both the broadband spectral energy distributions (SEDs) which were quasi-simultaneously obtained during the TeV flare and during the optical/X-ray outburst are well fit by using a single-zone synchrotron + synchrotron-self-Compton model. The satisfactory fitting requires a large beaming factor, i.e., $\delta \sim 25$ and $\delta \sim 20$ for the TeV flare and the optical/X-ray outburst, respectively, suggesting that both the optical/X-ray outburst and the TeV flare are from a relativistic jet. The size of the emission region of the TeV flare is three times larger than that of the optical/X-ray outburst, and the strength of the magnetic field for the TeV flare is ~ 14 times smaller than that of the X-ray/optical outburst, likely indicating that the region of the TeV flare is more distant from the core than that of the X-ray/optical outburst. The inverse Compton component of the TeV flare peaks around 1.3 GeV, but it is around 20 MeV for the X-ray/optical outburst, lower than that for the TeV flare by two orders of magnitude. The model predicts that the optical/X-ray outburst might be accompanied by a strong MeV/GeV emission, but the TeV flare may be not associated with the X-ray/optical outburst. The GeV emission is critical for characterizing the SEDs of the optical/X-ray outburst and the TeV flare. The predicted GeV flux is above the sensitivity of *Fermi*/LAT, and it could be verified with the observations by *Fermi*/LAT in the near future.

Key words: BL Lacertae objects: individual: W Comae — gamma-rays: observations — gamma-rays: theory — radiation mechanisms: non-thermal

1 INTRODUCTION

The continuum emission of active galactic nuclei (AGNs) is both highly luminous and rapidly variable, especially for a sub-class of blazars. The radiation of blazars is dominated by emission from a relativistic jet oriented close to the line of sight (Blandford & Rees 1978). Their broad band spectral energy distributions (SEDs) are characterized by two broad, well separated components. It is believed that the lower one is produced by the synchrotron process, and the higher one could be due to inverse Compton

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(IC) scattering of the same electron population (e.g., Ulrich et al. 1997; Urry 1999). According to the location of the synchrotron hump, blazars are classified as flat-spectrum radio quasars (FSRQs), low-frequency-peaked BL Lac objects (LBLs) with a synchrotron radiation peak in the IR/optical regime, and high-frequency-peaked BL Lac objects (HBLs) with a synchrotron radiation peak in the X-ray band (Giommi & Padovani 1994; Ulrich et al. 1997). The intermediate-frequency-peaked BL Lac objects (IBLs) fill in the gap between LBLs and HBLs.

Blazars show significant variability in multi-frequency, from radio to gamma-ray bands, even in the TeV gamma-ray band. Gamma-ray emission is an important emission component for the SEDs of blazars, since the radiation in this band is comparable to the total radiation power of the sources and even higher than that in the rest of the other energy bands. It plays an important role in understanding the radiation mechanisms and the emission regions of Blazars (e.g., Catanese & Weekes 1999). Considerable samples of GeV-TeV blazars have been obtained with both space-based instruments and ground-based Cherenkov telescopes. For example, the EGRET instrument on board the Compton Gamma Ray Observatory (CGRO) identified a sample of some MeV/GeV blazars. Most of them are FSRQs and LBLs (Hartman et al. 1999; Mattox et al. 2001). The imaging atmospheric Cherenkov telescopes (IACTs) have established a sample of more than 20 blazars as very high energy (VHE) γ-ray radiation sources. Almost all of them belong to HBLs. W Comae (W Com, ON 231, 1219+285), an IBL at redshift $z = 0.102$, has long been considered as a VHE gamma-ray source (Kerrick et al. 1995). More recently, a TeV flare of this object was detected with VERITAS, an array of four imaging atmospheric-Cherenkov telescopes (Acciari et al. 2008). This is the first TeV detection from an IBL source. In this paper, I investigate the properties of the VHE emission from this source.

The historic optical light-curve of W Com shows three major outbursts which peaked in March 1995, February 1996, and January 1997. The source brightness reached the highest magnitude in April 1998 ($R = 12.2$; Tosti et al. 1999; Massaro et al. 1999), which was never observed since 1940 [1]. It was about 3 times brighter than the optical outbursts observed in previous years and a factor of 60 brighter than the minimum brightness $B = 17.5$ in 1972 (Tosti et al. 1999; Massaro et al. 1999). A previously undetected high polarization was also observed at the same time (Tosti et al. 1999), which indicates a non-thermal origin of the optical outburst. The source was also detected in the infrared band by IRAS, the Infrared Astronomical Satellite (Impey & Neugebauer 1988).

In the X-ray band, W Com was observed by *Einstein*/IPC in June 1980 (Worrall & Wilkes 1990) and by ROSAT/PSPC in June 1991 (Lamer et al. 1996; Comastri et al. 1997), with detections of flux density $\sim 1\,\mu$Jy and $0.4\,\mu$Jy at 1 keV, respectively. The derived energy spectral index from the ROSAT/PSPC observation is $\alpha \sim 1.2$. The observation with XTE in a multi-wavelength campaign in February 1996 yielded only an upper limit (Maisack et al. 1997). The source was in a high state in the X-ray band during the strongest optical flare in 1998 (Tagliaferri et al. 2000). The observation with the *BeppoSAX* satellite derived a well-defined two-component feature in the X-ray spectrum, which is explained as a synchrotron component and an IC component (Tagliaferri et al. 2000; Böttcher et al. 2002). Moreover, the source showed significant variation in the soft X-ray band (0.1–4 keV), but no similar behavior in the hard X-ray band (4–10 keV).

In the gamma-ray band, W Com was first observed with CGRO/EGRET during 1991–1992. The observed gamma-ray spectrum is extremely hard, with $\alpha \sim 0.4 \pm 0.4$ (von Montigny et al. 1995; Sreekumar et al. 1996), even harder than that derived in 1995 when the source was in the brightest state in the EGRET band (Tagliaferri et al. 2000). The EGRET observation in February 1996 during a quasi-simultaneous multi-wavelength campaign shows that its brightness was weaker than that observed in November 1993 by a factor of 1.5 (Maisack et al. 1997). During April 1998 to May 1998 the source was in a high state in both the optical and X-ray bands, but the gamma-ray emission was only marginally detected by EGRET in March 1998, with a 2.7σ significance level (Böttcher et al. 2002). Observations with Whipple/IACT obtained some upper limits in the TeV band in 1993/94 (Kerrick et al. 1995) and 1995/96/99 (Horan et al. 2004). A preliminary 2σ upper limit was derived with STACEE in 1998 (Böttcher et al. 2002). Interestingly, a strong TeV flare was detected by VERITAS in the middle of

[1] Wolf (1916) reported $B = 11.5$ in 1901 and 1903.

March 2008 (Acciari et al. 2008), but was not accompanied by outbursts/flares in the X-ray and optical bands. An X-ray flare was detected about two weeks after the TeV flare (Acciari et al. 2008).

As mentioned above, the outburst/flare events of W Com in the optical/X-ray bands and in the TeV band seem not to happen simultaneously. It is generally believed that the X-ray/optical emission is produced by the synchrotron radiation. A puzzling question is if the TeV emission is from the same site as the X-ray/optical emission through an IC scattering by the same electron population as that of the synchrotron radiation. In this paper, I focus on this issue by fitting the broadband SEDs observed quasi-simultaneously during the TeV flare in 2008 and during the optical/X-ray outburst phase in 1998 with a single-zone synchrotron+synchrotron- self-Compton (SSC) model (Maraschi et al. 1992; Bloom & Marscher 1996), and reveal the different properties between the TeV flare and the X-ray/optical outburst by comparing the fitting results.

2 MODEL

The broad band SED for blazars is a double-peaked structure. It is believed that the lower one is produced by the synchrotron process, and the higher one could be due to IC scattering of the same electron population (e.g., Ulrich et al. 1997; Urry 1999). The IC scattering photon field could be from the synchrotron radiation itself, the so-called SSC model (Maraschi et al. 1992; Bloom & Marscher 1996) or from external radiation fields (EC), such as the broad line region (BLR; Sikora et al. 1994; Koratkar et al. 1998), accretion disk (Dermer et al. 1992), torus (BŁażejowski et al. 2000), and cosmic microwave background (CMB; Burbidge et al. 1974; Tavecchio et al. 2000). Since those external photon fields are very weak compared with the synchrotron radiation field for the BL Lac objects, I only consider a synchrotron + SSC model by assuming that the emission region is a homogeneous sphere with dimension R and the electron distribution in energy is a broken power law with indices p_1 and p_2 below and above the break energy $\gamma_b m_e c^2$,

$$N(\gamma) = \begin{cases} N_0 \gamma^{-p_1} & \gamma < \gamma_b, \\ N_0 \gamma_b^{p_2 - p_1} \gamma^{-p_2} & \gamma > \gamma_b, \end{cases} \quad (1)$$

where $p_{1,2} = 2\alpha_{1,2} + 1$, $\alpha_{1,2}$ are the spectral indices, and γ is the Lorentz factor of the electrons. The frequency of the synchrotron radiation is

$$\nu_{\rm syn} = \frac{4}{3} \nu_B \gamma^2 \frac{\delta}{1+z}, \quad (2)$$

where $\nu_B = 2.8 \times 10^6 B$ Hz is the Larmor frequency in magnetic field B (e.g., Ghisellini et al. 1996) and δ is the Doppler factor. The synchrotron emissivity $\epsilon_{\rm s}(\nu)$ is calculated with

$$\epsilon_{\rm s}(\nu) = \frac{1}{4\pi} \int_{\gamma_{\min}}^{\gamma_{\max}} d\gamma N(\gamma) P_{\rm s}(\gamma, \nu), \quad (3)$$

where $P_{\rm s}(\nu, \gamma)$ is the single electron synchrotron emissivity averaged over an isotropic distribution of pitch angles. It is calculated with (Crusius & Schlickeiser 1986; Ghisellini et al. 1988)

$$P_{\rm s}(\gamma, \nu) = \frac{3\sqrt{3}}{\pi} \frac{\sigma_{\rm T} c U_B}{\nu_B} g^2 \{K_{4/3}(g) K_{1/3}(g) - \frac{3}{5} g [K_{4/3}^2(g) - K_{1/3}^2(g)]\}, \quad (4)$$

where $g = \nu/(3\gamma^2 \nu_B)$, K_α is the modified α-order Bessel function, $\sigma_{\rm T}$ is the Thomson cross-section, and $U_B = \frac{B^2}{8\pi}$ is the magnetic field energy density. The synchrotron radiation field $I_{\rm s}(\nu)$ is calculated by the transfer equation,

$$I_{\rm s}(\nu) = \frac{\epsilon_{\rm s}(\nu)}{k(\nu)} [1 - e^{-k(\nu) R}], \quad (5)$$

where $k(\nu)$ is the absorption coefficient (Ghisellini & Svensson 1991).

In the SSC scenario, the relativistic electrons interact with synchrotron radiation photons through the IC scattering. The IC emissivity is calculated by

$$\epsilon_c(\nu_c) = \frac{\sigma_T}{4}\int_{\nu_i^{\min}}^{\nu_i^{\max}} \frac{d\nu_i}{\nu_i}\int_{\gamma_1}^{\gamma_2} \frac{d\gamma}{\gamma^2\beta^2} N(\gamma) f(\nu_i, \nu_c)\frac{\nu_c}{\nu_i} I_{\rm s}(\nu_i), \tag{6}$$

where ν_i is the frequency of the incident photons emitted by the synchrotron radiation between $\nu_i^{\min}$ and $\nu_i^{\max}$, $\beta = v/c$, γ_1 and γ_2 are the lower and upper limits of the scattering electrons, and $f(\nu_i, \nu_c)$ is the spectrum produced by scattering monochromatic photons of frequency ν_i with a single electron (e.g., Rybicki & Lightman 1979). The medium is transparent for the IC radiation field, so I simply derived $I_c(\nu_c) = \epsilon_c(\nu_c)R$.

Assuming that $I_{\rm s,c}$ is an isotropic radiation field, the monochromatic luminosity around the source is obtained by

$$L(\delta\nu) = 4\pi^2 R^2 I_{{\rm s},c}(\nu)\delta^3. \tag{7}$$

Then the observed flux density is given by

$$F(\nu_{\rm obs}) = \frac{4\pi^2 R^2 I_{{\rm s},c}(\nu)\delta^3(1+z)}{4\pi D^2}, \tag{8}$$

where D is the luminosity distance of the source and $\nu_{\rm obs} = \nu\delta/(1+z)$.

In the GeV-TeV regime, the Klein-Nishina effect could be significant. It makes the IC spectrum have a high-energy cut-off. I take this effect into account by using a step function for the energy dependence of the cross section, $\sigma = \sigma_{\rm T}$ for $\gamma x \le 3/4$ and $\sigma = 0$ otherwise, where $x = h\nu/m_{\rm e}c^2$ (e.g., Tavecchio et al. 1998; Chiaberge & Ghisellini 1999). Since W Com is located at $z = 0.102$, the absorption by the infrared background light and CMB during the gamma-ray photons propagating to Earth is also considered (Stecker et al. 2006).

3 NUMERICAL RESULTS

I fitted the broadband SEDs which were observed quasi-simultaneously during the TeV flare in 2008 and during an optical/X-ray outburst phase in 1998. The SED data of the optical/X-ray flare are taken from Tagliaferri et al. (2000, for the optical and the X-ray data) and Böttcher et al. (2002, for the radio and the EGRET data). The observed data of the TeV flare in 2008 are from Acciari et al. (2008) and the references therein. The size of the emission region is estimated by the variability timescale t with $R = ct\delta$, where c is the speed of light. The t value is taken as ten hours for the X-ray/optical outburst and one day for the TeV flare according to the timescales of the X-ray flare in 1998 and the TeV flare in 2008 (Böttcher et al. 2002; Acciari et al. 2008).

The well-sampled SED data in the radio, optical, X-ray, and TeV bands for the 2008 TeV flare place strong constraints on the physical parameters of the model. Although no TeV detection was made during the 1998 optical/X-ray outburst, the X-ray spectrum measured by *BeppoSAX* during the optical/X-ray outburst reveals a clear two-component feature, i.e., a synchrotron component and an IC component (Tagliaferri et al. 2000; Böttcher et al. 2002), which also reliably confines the model parameters. The fitting results are shown in Figure 1, and the model parameters are reported in Table 1. The SED derived by the model is corrected for $\gamma\gamma$ absorption according to the baseline infrared background light case of Stecker et al. (2006). It is found that the model fits the SEDs well. Large beaming factors, $\delta \sim 25$ and $\delta \sim 20$ are required to fit the SEDs, suggesting that both the optical/X-ray outburst and the TeV flare are from a relativistic jet. It is interesting that the size of the emission region of the TeV flare is three times larger than that of the optical/X-ray outburst, and the strength of the magnetic field for the TeV flare is ~ 14 times smaller than that of the X-ray/optical outburst, likely indicating that the region of the TeV flare is further away from the core than that of the X-ray/optical outburst. The IC component of the TeV flare peaks around 10^{24} Hz, but it is around 10^{22} Hz for the X-ray/optical outburst, lower than that for the TeV flare by two orders of magnitude.

Table 1 Fitting Parameters

Epoch	Syn. peak(Hz)	α_1	α_2	δ	B (G)	R (cm)
2008	5.2×10^{14}	0.54	1.63	24.5	0.01	6.35×10^{16}
1998	1.0×10^{14}	0.2	1.53	19.4	0.14	2.1×10^{16}

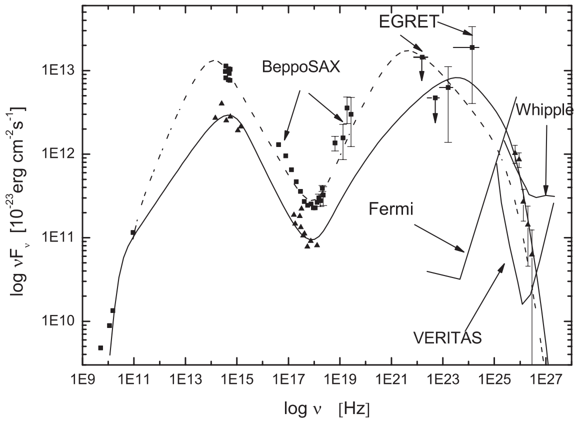

Fig. 1 Broadband SEDs of the optical/X-ray outburst in 1998 (*squares*) and of the TeV flare in 2008 (*triangles*) with the model fits. The SED data of the optical/X-ray outburst are taken from Tagliaferri et al. (2000, for the optical and the X-ray data) and Böttcher et al. (2002, for the radio and the the EGRET data). The observed data of the TeV flare in 2008 are from Acciari et al. (2008) and the references therein. The model parameters are $\delta = 24.5$, $B = 0.01$ G, and $R = 6.35 \times 10^{16}$ cm for the fit to the SED of the 2008 TeV flare (*solid line*), and $\delta = 19.4$, $B = 0.14$ G, and $R = 2.1 \times 10^{16}$ cm for the fit to the SED of the 1998 optical/X-ray outburst (*dashed line*). The sensitivity curves for Whipple, VERITAS, and Fermi are also shown as marked in the figure.

4 CONCLUSIONS AND DISCUSSION

The broadband SEDs observed quasi-simultaneously during the TeV flare in 2008 and during the optical/X-ray outburst phase in 1998 are fitted with the single-zone synchrotron+SSC model. In the model, the IC radiation of the external photon fields (EC) is not taken into account since the CMB/BLR/torus/accrection disk photon fields are weak compared with the synchrotron radiation field for a BL Lac object. The results show that the SEDs can be described by the synchrotron + SSC leptonic jet model.

The satisfactory fitting requires a large beaming factor, i.e., $\delta \sim 25$ and $\delta \sim 20$ for the TeV flare and the optical/X-ray outburst, respectively, suggesting that both the optical/X-ray outburst and the TeV flare are from a relativistic jet. The strength of the magnetic field for the TeV flare is ~ 14 times smaller than that of the X-ray/optical outburst, likely indicating that the emission region is more distant from the core in 2008 than it was in 1998, since the magnetic field *B* decreases along the jet. Electrons can be reaccelerated after leaving the inner jet, hence the peak frequencies of synchrotron radiation in the kiloparsec-scale jets could be more than 100 times larger than those in the inner jets (e.g., Bai & Lee 2003). Our results favor this idea.

Almost the entire flare in 2008, which lasted four nights, was recorded by VERITAS. The simultaneous observations in the X-ray band did not detect any outburst/flare events. An X-ray flare following the TeV flare after two weeks was observed, with a peak flux four times higher than that observed during the TeV flare. This fact shows that the TeV flare and the X-ray flare may not be simultaneous. As shown in Figure 1, the IC component peaks around 10^{22} Hz for the SED during an optical/X-ray outburst, which is two orders of magnitudes lower than that for the SED during the TeV flare. The GeV observation thus is critical for characterizing the SEDs of both the optical/X-ray outburst and the TeV flare. The fitting results suggest that the optical/X-ray outburst may accompany a strong MeV/GeV flare. The predicted flux at GeV is far above the sensitivity of *Fermi*/LAT, and W Com is a selected target for *Fermi*/LAT. The model could be verified with the *Fermi*/LAT observation.

In the TeV band, the predicted TeV flux by the model for the optical/X-ray outburst in 1998 is lower than the sensitivity of Whipple/IACT. This may be the reason why no detection was obtained with Whipple/IACT in 1998. Although the predicted TeV flux is marginally over the sensitivity of VERITAS, it is much lower than the observed TeV flux in 2008.

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