VERITAS Discovery of >200 GeV Gamma-ray Emission from the Intermediate-frequency-peaked BL Lac Object W Comae

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ABSTRACT

We report the detection of very high-energy γ-ray emission from the intermediate-frequency-peaked BL Lacertae object W Comae ($z = 0.102$) by VERITAS, an array of four imaging atmospheric-Cherenkov telescopes. The source was observed between January and April 2008. A strong outburst of γ-ray emission was measured in the middle of March, lasting for only four days. The energy spectrum measured during the two highest flare nights is fit by a power-law and is found to be very steep, with a differential photon spectral index of $\Gamma = 3.81 \pm 0.35_{\rm stat} \pm 0.34_{\rm syst}$. The integral photon flux above 200 GeV during those two nights corresponds to roughly 9% of the flux from the Crab Nebula. Quasi-simultaneous Swift observations at X-ray energies were triggered by the VERITAS observations. The spectral energy distribution of the flare data can be described by synchrotron-self-Compton (SSC) or external-Compton (EC) leptonic jet models, with the latter offering a more natural set of parameters to fit the data.

Subject headings: BL Lacertae objects: individual (W Comae) — gamma-rays: observations

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1. Introduction

The blazars detected at very high energies (VHE, $E > 100\,\mathrm{GeV}$) by ground-based imaging atmospheric-Cherenkov telescopes (IACTs) are extreme objects in the active galactic nuclei (AGN) population. Typically these sources show core-dominated emission, and they are characterized by rapid variability and strong broadband continuum emission ranging from the radio band to the X-ray band. Multi-wavelength data on blazars reveal that their spectral energy distribution (SED) is characterized by two broad, well-separated "humps" arising from synchrotron (low-energy) and inverse-Compton (IC) or hadronic emission (high-energy). Blazars are categorized into different sub-classes based on the frequencies at which these emission components reach a maximum. Flat-spectrum radio quasars (FSRQs) and low-frequency-peaked BL Lacs (LBLs) are generally seen to have low-frequency, synchrotron peaks in the IR/optical regime, whereas high-frequency-peaked BL Lacs (HBLs) exhibit peaks in the X-ray band, in several cases at energies of ∼100 keV or higher. Intermediate-frequency-peaked BL Lacs (IBLs) bridge the gap between LBLs and HBLs. The properties of the broad sub-classes of blazars, the luminosity-versus-frequency trends and possible physical explanations are discussed by Ghisellini & Tavecchio (2008).

Gamma rays are an important component of the SED of blazars; the integral power in the γ-ray waveband is comparable or higher than that in the rest of the electromagnetic spectrum (from radio to X-rays). There are 65 blazars detected at MeV/GeV energies by the EGRET instrument on board the *Compton Gamma Ray Observatory (CGRO)* (Mattox et al. 2001; Hartman et al. 1999) and several of the other EGRET sources also have likely blazar counterparts. Ground-based IACTs have established ∼20 blazars as emitters of VHE γ-radiation; see for example Wakely & Horan (2007). While the blazars detected at MeV/GeV energies tend to be largely FSRQs (and some LBLs), almost all VHE blazars belong to the class of HBLs, the only exceptions being the LBLs BL Lacertae (Albert et al. 2007a), S5 0716+71 (Teshima 2008) and the FSRQ 3C 279 (Teshima et al. 2007).

The IBL W Comae (W Com) at a redshift of $z = 0.102$ has long been an object of interest for VHE observatories. W Com was discovered at radio frequencies (Biraud 1971) and later detected at X-ray energies by the *Einstein* Imaging Proportional Counter in June 1980 (Worrall & Wilkes 1990). Data taken with the *BeppoSAX* satellite in 1998 (Tagliaferri et al. 2000) clearly showed that the transition between the low- and high-energy peaks in the SED occurs around ∼4 keV. In April-May 1998, an exceptional optical outburst was detected from W Com showing rapid variability on time scales of hours (Massaro et al. 1999).

At γ-ray energies, W Com was detected by EGRET in the 100 MeV−10 GeV band (Hartman et al. 1999) and in a re-analysis of the data up to 25 GeV (Dingus & Bertsch 2001). Due to its rather hard EGRET spectrum (photon spectral index $\alpha = 1.73 \pm 0.18$), with no sign of spectral

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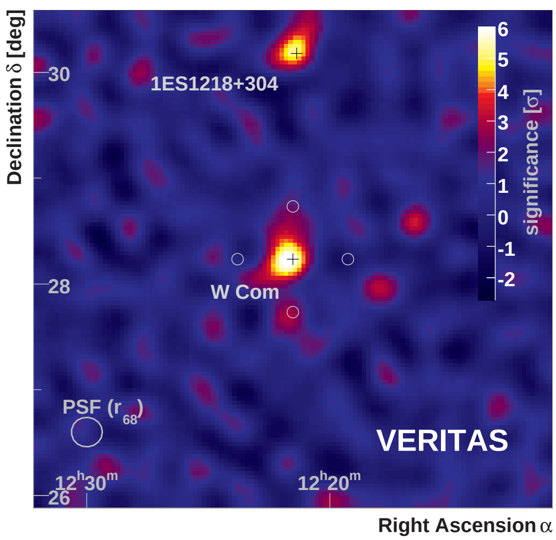

Fig. 1.— Sky map of significances of the whole data set (*standard cuts*, oversampling radius of 0.15°). The background is estimated using the ring background model (Berge et al. 2007). The excess ∼2° North of W Com (cross) corresponds to 1ES 1218+304 (cross) and demonstrates the capability of VERITAS to detect sources at the edge of the field of view of the camera. The telescope tracking positions in wobble mode (open circles) and the angular resolution (PSF) are indicated as well.

cut-off (Hartman et al. 1999), the source became even more interesting for VHE observations. However, W Com was not detected by the Whipple IACT above 300 GeV in 1993/94 (Kerrick et al. 1995) and 1995/96/98 (Horan et al. 2004), nor by the solar heliostat Cherenkov telescope STACEE (Scalzo et al. 2004). In this paper we report the discovery of VHE γ-ray emission from W Com with VERITAS.

2. VERITAS and Swift Observations and Results

VERITAS consists of four 12 m diameter IACTs and is located at the basecamp of the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona at an altitude of 1280 m. It detects the Cherenkov light emitted by an extensive air shower (initiated by a VHE γ-ray photon or cosmic ray entering the Earth's atmosphere) using a 499-pixel photomultiplier camera located in the focal plane of each telescope. The array is sensitive to γ-rays in the energy range from ∼100 GeV to ∼30 TeV. Observations are performed in moonless nights in the "wobble" mode of operation, where the telescopes are pointed to positions offset by ±0.5° (alternating in direction) with respect to the source position, to allow for a simultaneous background estimation. More details about VERITAS, the data calibration and the analysis techniques can be found in Acciari et al. (2008).

Only shower images which pass certain quality cuts are considered in the event reconstruction (image size ≥ 500 digital counts (dc)[1]; distance between the image center of gravity and the center of the camera ≤ 1.43°). The γ/hadron separation cuts used in this analysis are based on the width and length of the recorded images (Acciari et al. 2008) and were optimized *a priori* on Crab Nebula data for a source with a flux at the 5%-level of the Crab Nebula. We refer to these as *standard cuts*. An event is considered to fall into the signal (ON) region, if the squared angular distance $\Delta\theta^2$ between the reconstructed event direction and the W Com position is less than 0.0125 deg^2. The background is estimated from different regions of equal size positioned at the same radial distance from the camera center as the ON region (Berge et al. 2007). This background model, referred to as the "reflected region model", is used unless otherwise stated. Since the energy spectrum of W Com is found to be very steep (see below) a second set of cuts (optimized on Crab Nebula data for low energies of $E \leq 200$ GeV) is used to derive the energy spectrum and the light curve. These *a posteriori* cuts are referred to as *soft cuts* in this paper and use an image size ≥ 250 dc and an angular distance to the source position of $\Delta\theta^2 \leq 0.02$ deg^2. All results obtained with the *soft cuts* are in good agreement with the ones obtained using the *standard cuts*.

VERITAS observed W Com from January to April 2008 for a total of 39.5 hours (deadtime corrected) after run quality selection. The zenith-angle range of the observations was $3° - 45°$ with an average of 19°, corresponding to an analy-

[1] The photomultiplier pulses are integrated within a time window of 24 ns duration. One digital count corresponds to approximately 5 photoelectrons.

sis energy threshold[2] of 260 GeV (*standard cuts*) and 180 GeV (*soft cuts*). In the entire data set, 111 excess events (543 ON events and 432 normalized OFF events, normalization $\alpha = 0.111$) are detected from the direction of W Com using the *standard* cuts, corresponding to a statistical significance of 4.9 standard deviations ($4.9\,\sigma$), calculated following Li & Ma (1983). The sky map showing W Com and the known VHE blazar 1ES 1218+304[3] (Albert et al. 2006; Fortin et al. 2007) located in the same field of view of the dedicated W Com observations is shown in Fig. 1. The mean position of the W Com excess is derived by fitting a 2D Gaussian function to the uncorrelated excess sky map and is found to be compatible within errors with the nominal position of W Com.

Almost the entire excess from W Com (> 70%) is recorded during a strong flare, which occured during four nights in the middle of March (Swordy 2008); see Fig. 2. The measured excess of the whole corresponding observation period – modified Julian date (MJD) 54528.4 to 54540.4 – corresponds to a statistical significance of $6.3\,\sigma$ (*standard cuts*, 85 excess events) and $8.6\,\sigma$ (*soft cuts*, 275 excess events). Correcting for 8 trials (four observations periods and two sets of cuts) results in $5.9\,\sigma$ and $8.3\,\sigma$, respectively. No statistically significant excess is measured in the remaining data set. A fit of a constant function to the whole night-by-night light curve (January to April) results in a probability of constant emission of $2.1 \cdot 10^{-4}$. In order to estimate the time scale of the flux variations the light curve of the flare nights (see inlay of Fig. 2) is modeled by the function $\Phi(t) = \Phi_0 \times \exp\left(-(t-t_0)^2/\sigma_{\mathrm{t}}^2\right)$ with the flare occurring at $t_0 = 54538.6 \pm 0.2$ MJD with the characteristic time scale of $\sigma_{\mathrm{t}} = 1.29 \pm 0.28$ days. No significant flux variations are measured within individual nights.

A differential energy spectrum is derived for the two highest flare nights. The spectrum is shown in Fig. 3 and is well fit ($\chi^2/\mathrm{dof} = 2.9/3$) by a power-law function $\mathrm{dN/dE} = \mathrm{I_0} \times (\mathrm{E}/400\,\mathrm{GeV})^{-\Gamma}$, with $I_0 = (2.00 \pm 0.31_{\mathrm{st}}) \times 10^{-11}\,\mathrm{cm^{-2}\,s^{-1}\,TeV^{-1}}$ and $\Gamma = 3.81 \pm 0.35_{\mathrm{st}}$. The integral photon flux

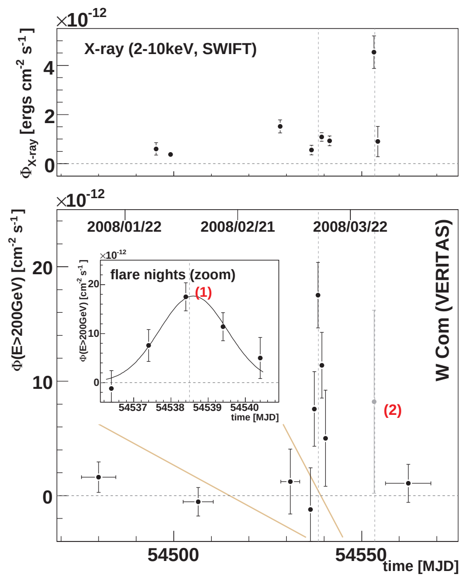

Fig. 2.— **Lower panel:** The light curve $I(E > 200\,\mathrm{GeV})$ is shown (*soft* cuts, assuming a spectral shape of $\mathrm{dN/dE} \propto \mathrm{E}^{-\Gamma}$ with $\Gamma = 3.8$). Each flux point corresponds to one observation period (defined by ~3 weeks of operation between two full-moon phases), with the exception of the flare around MJD 54538 (1) for which a night-by-night binning is used (see inlay for details; the fitted model light curve is described in the text). **Upper panel:** The X-ray flux as measured by Swift for the same time period. The vertical lines are shown for easier comparison. The simultaneous VERITAS/Swift measurements around MJD 54553.3 (2) during a high X-ray flux level is discussed in the text.

above 200 GeV is calculated to be $\Phi_{E>200\,\mathrm{GeV}} = (1.99 \pm 0.07_{\mathrm{st}}) \times 10^{-11}\,\mathrm{cm^{-2}\,s^{-1}}$, corresponding to 9% of the flux measured from the Crab Nebula above the same energy. The systematic errors on the normalization constant and the photon index for this low-energy regime are estimated to be $\Delta I_0/I_0 = 25\%$ and $\Delta\Gamma/\Gamma = 9\%$, respectively.

Simultaneous Swift observations of W Com were performed for a total duration of 11.6 h. Swift comprises a UV instrument UVOT and X-ray instruments XRT and BAT (Gehrels et al. 2004). Data reduction and calibration are performed with the *HEAsoft 6.4* package[4] and the

[2] The energy threshold is defined as the energy corresponding to the peak detection rate for a Crab-like spectrum.

[3] A significant VHE γ-ray excess was recorded from 1ES 1218+304 during the dedicated W Com observations which will be addressed in a forthcoming paper.

[4] http://heasarc.gsfc.nasa.gov/lheasoft/

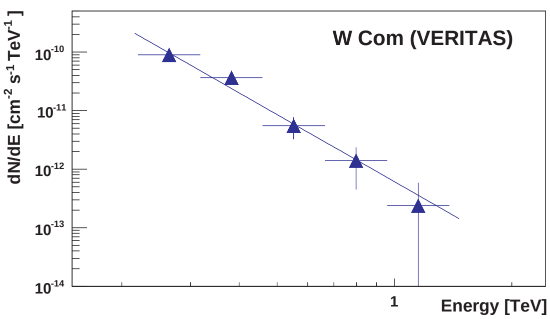

Fig. 3.— Differential energy spectrum of W Com (*soft cuts*), derived from the two highest flare nights: label (1) in Fig. 2. The parameters of the fitted power-law function (line) are summarized in the text.

XRTPIPELINE tool. All XRT data presented here were taken in Photon Counting (PC) mode. Standard filtering criteria are applied. Photon pile-up effects are negligible in the data. All energy spectra are fit with an absorbed power law using *XSPEC 12.4*. A galactic column density of $N_{\rm H} = 1.88 \cdot 10^{20}\,{\rm cm}^2$ was assumed (Dickey & Lockman 1990). No significant deviation from a power law spectral shape is found within the limited statistics. UVOT observations were taken over the six photometric bands of V, B, U, UVW1, UVM2, and UVW2 (Poole et al. 2008). The UVOTSOURCE tool is used to extract counts, correct for coincidence losses, apply background subtraction and calculate the source flux. The source fluxes are de-reddened using the interstellar extinction curve in Fitzpatrick (1999).

The light curve of the X-ray flux is shown in Fig. 2, upper panel. No change in spectral slope could be detected when comparing results for individual nights. An X-ray flux at a level roughly 4 times higher than the flux observed during the VHE flare was observed around MJD 54553.3 (see Fig. 2, top panel). VERITAS also observed W Com during this night for ~40 min but the data do not pass the standard quality selection[5]. Nevertheless, since the VERITAS data (MJD 54553.3) are simultanenous with the X-ray flare the flux derived from these data (including an additional 50% systematical error) is shown for reference in Fig. 2, label (2). The 99.9% c.l. upper limit (assuming an underestimation of the count rates by 50%) is calculated to be ~2 times higher than the peak flux measured during the VHE flare. Although no detailed conclusions can be drawn, a linear X-ray/TeV flux correlation does not seem likely.

[5]Showing a cosmic ray triggerrate ~27% lower than expected due to non-optimal weather conditions – with the maximum allowed deviation being 20%.

3. Modeling and Discussion

The VERITAS data taken at MJD 54538.4 and 54539.4 are used to model the SED of W Com (see Fig. 4) together with the simultaneous SWIFT XRT/UVOT (MJD 54539.4) and optical AAVSO data (MJD 54540, Bedient (2008)), as well as archival radio data. The following model curves are corrected for $\gamma\gamma$ absorption by the extragalactic background light according to the "best fit" model of Kneiske et al. (2004). The SED can be fit by a simple one-zone SSC model, using the equilibrium version of the code of Böttcher & Chiang (2002b). Here an ad-hoc non-thermal electron injection spectrum with particle index q and total particle injection luminosity $L_{\rm inj}$ is balanced self-consistently with radiative cooling from synchrotron and Compton emission. The best fit to the SED is shown in Fig. 4 as a solid line. The parameters of the fit are: $\gamma_1 = 450$, $\gamma_2 = 4.5 \cdot 10^5$, $q = 2.2$, $L_{\rm inj} = 2.8 \cdot 10^{45}\,{\rm erg/s}$, a magnetic field of $B = 0.007\,{\rm G}$, a doppler factor of $\delta = 30$ and a size of the emission region of $R = 10^{17}\,{\rm cm}$. The wide separation of the SED peaks, together with the very low X-ray flux, require an unusually low magnetic field in order to allow for sufficiently high particle Lorentz factors to produce the observed VHE γ-ray flux. The ratio between the magnetic and electron energy densitiy is $\sigma = 1.3 \cdot 10^{-3}$. The light crossing time $\tau = R/(c \cdot \delta) \approx 1.3\,{\rm d}$ matches the time scale observed in the VHE flare (compare Fig. 2), but it is relatively large compared with the extremely rapid VHE variability on time scales of 2 to 10 minutes seen in other TeV blazars at higher flux levels (Albert et al. 2007b; Aharonian et al. 2007).

The SED was also fit by a self-consistent model that contains both SSC emission and an EC component, similar to the model of (Inoue & Takahara 1996). The external photons are assumed as steady-state blackbody radiation peaking in the near-infrared (radius 1800 Schwarzschild radii, 0.4% of the Eddington Luminosity). The particles are accelerated by diffusive shock acceleration and the maximum electron Lorentz factor $\gamma_{\rm max}$ is determined by competition between acceleration and radiative cooling. As for the SSC fit, a cooling break in the electron spectrum is assumed to occur at the energy where the cooling time becomes shorter than the light crossing time of the emission region. Finally, we assume that the electron distribution has some minimum Lorentz factor $\gamma_{\rm min}$ from some unknown injection process. The power-law slope of the electron spectrum (without the cooling break) is parameterized by $\rm dN/dE \propto E^{-s}$, where the free parameter s is expected to vary between 2.3 (for canonical first-order Fermi ultra-relativistic shock acceleration) and 2.0 (for canonical non-relativistic first order-Fermi acceleration by a strong shock). However, it should be noted that relativistic shocks could produce much harder energy spectra (Stecker et al. 2007).

A reasonably good fit (see Fig. 4) is obtained taking $B = 0.3\,\rm G$, $\delta = \Gamma = 30$, $\sigma = 1.0$ (assuming equipartition), $\gamma_{\rm min} = \Gamma = 30$ and $R = 1.76 \times 10^{16}\,\rm cm$. To match the inferred shape of the electron spectrum, rather inefficient particle acceleration is invoked (e.g., with $u_{\rm shock} = 0.1\,c$ in the bulk frame and the ratio of the electron scattering mean-free-path to the Bohm limit of 3000) with an electron spectrum with index $s = 2.0$. For this choice of parameters, the model gives an acceleration time (equal to the cooling time) at the maximum electron energy of 7.2 min. Assuming that the emission region of radius R is comoving with the jet, the light crossing time for these parameters is $\tau = 330$ min. This value is closer to the typical variability time scales of other VHE blazars and consistent with our observed lightcurve.

The synchrotron proton blazar (SPB) model from Böttcher et al. (2002a) fitted to data of the 1998 W Com campaign is also shown for reference in Fig. 4.

4. Summary & Conclusion

VERITAS detected VHE γ-ray emission from W Com with a statistical significance of 4.9 standard deviations for the entire data set (January to April 2008). A strong outburst was observed

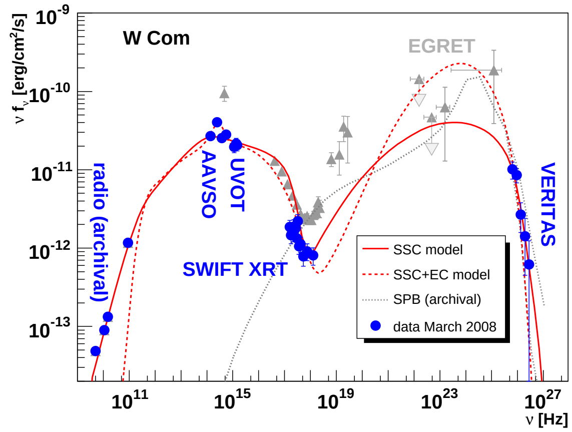

Fig. 4.— Quasi-simultaneous SED of W Com, including the VERITAS flare data (MJD 54538.4 and 54539.4, see Fig. 3), the Swift XRT/UVOT data (MJD 54539.4) and the V and I band data (MJD 54540) from AAVSO (Bedient 2008). The radio data are non-simultaneous and the same as in Böttcher et al. (2002a). Details of the SSC and SSC+EC model fits (see legend) are described in the text. The hadronic SPB model curve 1 from Böttcher et al. (2002a) is shown for reference. Archival data (optical, X-ray and 1998 EGRET data) are shown as grey points for comparison, see references in Böttcher et al. (2002a).

in March 2008 with a statistical significance of > 8 standard deviations, that lasted for only four days. In addition to W Com, a second extragalctic source (the VHE blazar 1ES 1218+304) is detected in the same field of view – for the first time in VHE γ-ray astronomy.

W Com is the first VHE-detected blazar of the IBL class. The extension of the VHE catalog to the FRSQ, LBL and IBL classes will play a major role in our understanding of blazar populations and dynamics. The quasi-simultaneous SED of W Com at the time of the VHE outburst can be modeled with a simple one-zone SSC model. However, an unusually low magnetic field of $B = 0.007\,\rm G$ (more than an order of magnitude lower than typically found in the modeling of other BL Lac-type blazars) and a small ratio of the magnetic field to electron energy density of $\sigma = 1.3 \cdot 10^{-3}$ are required. An EC model with more natural parameters ($B = 0.36\,\rm G$ and $\sigma = 1$) provides a good fit and could account for shorter variability time scales. Our model results agree with the expectation that for IBLs (and LBLs) the higher optical luminosity plays an important role in providing the seed population for IC scattering.

The IBL W Com will be an excellent target for future observations at GeV energies with GLAST and in the VHE regime with IACTs, including correlated GeV/TeV variability studies.

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