Multiwavelength observations of a TeV-Flare from W Com

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***Abstract*. We report results from an intensive campaign of multiwavelength observations of the intermediate-frequency-peaked BL Lacertae object W Com (z=0.102) during a strong outburst of very high energy (VHE; E $>$ 180 GeV) gamma-ray emission in June 2008. The initial detection of this VHE flare by VERITAS, an array of four 12-m diameter imaging atmospheric-Cherenkov telescopes, was followed by observations in high-energy gamma rays (AGILE, E $>$ 100 MeV), X-rays (*Swift*), optical and radio wavelengths. The VHE gamma-ray signal was detected by VERITAS on June 7-8 with a flux about three times brighter than during the discovery of VHE gamma-ray emission from W Com by VERITAS in March 2008. A detailed study of the spectral energy distribution of W Com during this flare, including theoretical work, will be presented.**

***Keywords*: gamma-ray observatory; blazars; W Com**

I. Introduction

W Com is an intermediate-frequency-peaked BL Lac (IBL) at a redshift of $z = 0.102$. The object was discovered in high-energy gamma rays (from 100 MeV to 10 GeV) by EGRET [11] and in very high energy gamma rays in March 2008 during a strong outburst of about 4 days duration by VERITAS [1]. The broadband spectral energy distribution (SED) of W Com is characterized by two peaks, arising from synchrotron radiation at radio to X-ray frequencies and high energy emission due to inverse Compton scattering or hadronic interactions at hard X-ray to gamma-ray energies. The X-ray and gamma-ray emission from W Com has been found to be variable on a timescale of hours to days [16].

Here we present contemporaneous observations of W Com during a second strong flare in June, 2008 with VERITAS, AGILE, and *Swift*.

II. Observations and Results

A. VERITAS

VERITAS is an array of four imaging atmospheric-Cherenkov telescopes located at the Fred Lawrence Whipple Observatory in southern Arizona. It combines a large effective area (up to 10^5 m^2) over a wide energy range (100 GeV to 30 TeV) with good energy (15-20%) and angular ($\approx$ 0.1°) resolution. The field of view of the VERITAS telescopes is 3.5°. The high sensitivity of VERITAS enables the detection of sources with a flux of 1% of the Crab Nebula in less than 50 hours of observations. For more details on the VERITAS instrument, see e.g. [17].

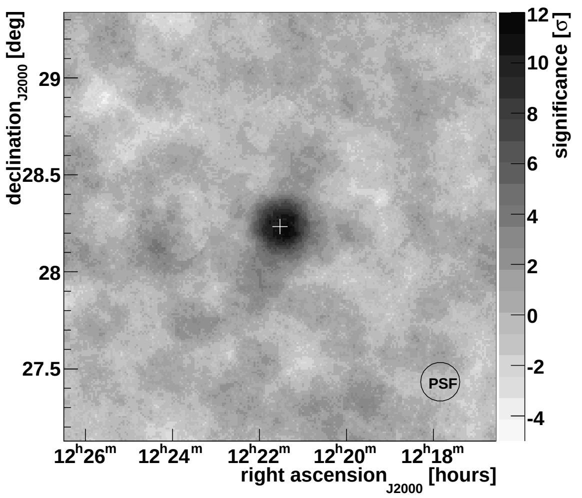

Fig. 1. VERITAS significance map of the region around W Com for MJD 54624.16 to 54625.24. The background is estimated using the reflected region model. The position of W Com derived from radio data is indicated by a white cross. The circle at the bottom right indicates the angular resolution of the VERITAS observations.

VERITAS observed the sky around W Com for about four hours in June 2008. All observations passed run quality selection criteria, which remove data taken during bad weather or with hardware-related problems. Data were taken in wobble mode, wherein the source was positioned at a fixed offset from the camera center. Parts of the observations were undertaken in moonlight conditions, where the elevated background light levels lead to a lower flux sensitivity and higher energy threshold for the detection of γ-rays. The different elevations combined with the continuously changing background light conditions due to the moon results in a wide range of energy thresholds from 180 to 420 GeV[1] for the present observations. Table I lists observation times, elevation range, and background light conditions.

[1]The energy threshold is defined as the peak of the differential counting rate for a Crab Nebula-like spectrum.

TABLE I
DETAILS OF THE VERITAS OBSERVATIONS OF W COM IN 2008 JUNE. FLUXES AND UPPER FLUX LIMITS ARE GIVEN AT THE 99% CONFIDENCE LEVEL FOR AN ENERGY THRESHOLD OF 200 GEV.

MJD	elevation range	observation time [min]	average pedestal variations [dc][2]	significance [σ]	flux or upper flux limit [$cm^{-2}s^{-1}$]
54624.16 - 54624.23	53-73°	100.2	7.8-8.0	8.9	$(5.0 \pm 0.8) \times 10^{-11}$
54625.17 - 54625.24	49-68°	100.2	8.1-9.7	7.9	$(6.2 \pm 1.2) \times 10^{-11}$
54626.18 - 54626.20	59-60°	32.0	12.2-12.3	-1.0	$< 3.15 \times 10^{-11}$

The VERITAS data analysis steps consist of image calibration and cleaning, second-moment parameterization of these images [13], stereoscopic reconstruction of the event impact position and direction, gamma-hadron separation, spectral energy reconstruction (see e.g. [14]) as well as the generation of photon sky maps. The majority of the far more numerous background events are rejected by comparing the shape of the event images in each telescope with the expected shapes of gamma-ray showers modeled by Monte Carlo simulations[3]. These *mean-reduced-scaled width* and *mean-reduced-scaled length* cuts (see definition in [14]), and an additional cut on the arrival direction of the incoming gamma ray (Θ^2) reject more than 99.9% of the cosmic-ray background while keeping 45% of the gamma rays. The cuts applied here are: integrated charge per image $>$ 400 digital counts ($\approx$75 photoelectrons), $-1.2 <$ mean-reduced-scaled width/length < 0.5, and $\Theta^2 < 0.015$ deg^2. The background in the source region is estimated from the same field of view using the "reflected-region" model [5].

VERITAS detected a significant flux of high-energy gamma rays from W Com for the entire data set (June 7-9 2008). A total of 117 excess events (195 ON events and 78 normalized OFF events, normalization factor $\alpha = 0.10$) have been measured. This corresponds to a total significance of 10.3 standard deviations, calculated following equation 17 in [15]. The daily significances and fluxes above 200 GeV can be found in Table I. W Com was not detected on June 9 2008 (MJD 54626), but observations were restricted to 32 min due to bright background light levels caused by the moon. The sky around W Com in high-energy gamma rays for the June 7-8 2008 observations is shown in Figure 1. The region around the TeV-blazar 1ES 1218+304 [3], located about 2° north of W Com, has been excluded from the background estimation.

The differential photon spectra between 180 GeV and 3 TeV for the combined measurements from June 7 and 8 2008 are shown in Figure 2. The shape is consistent with a power law $\mathrm{dN/dE = C \times (E/0.4GeV)^{-\Gamma}}$ with a photon index $\Gamma = 3.68 \pm 0.22_{stat}$ and a flux normalization constant C = $(6.5 \pm 0.9_{stat}) \times 10^{-11}$ $cm^{-2}s^{-1}TeV^{-1}$. The χ^2 of the fit is 3.27 for 5 degrees

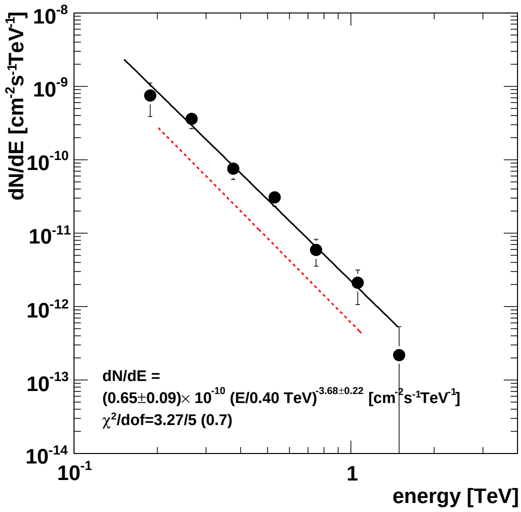

Fig. 2. Differential energy spectrum for W Com for MJD 54624.16 to 54625.24 (June 7-8 2008). The markers indicate measured data points, the continuous line a fit assuming a power-law distribution. The spectral energy distribution measured by VERITAS in March 2008 [1] is indicated by a dashed line.

of freedom[4]. For comparison, the flare in high-energy gamma rays from W Com in March 2008 is well fit by the same power law with $\Gamma = 3.81 \pm 0.35_{stat}$ and C = $(2.00 \pm 0.31_{stat}) \times 10^{-11}$ $cm^{-2}s^{-1}TeV^{-1}$.

B. AGILE

The Gamma-Ray Imaging Detector (GRID, 30 MeV - 30 GeV) onboard the high energy astrophysics satellite AGILE ([19], [20]) observed W Com uninterruptedly from 9 (18:00 UT) to 15 (12:00 UT) June, 2008. Preliminary and partial results of this observation were reported in [22]. The GRID data were analyzed using the AGILE standard pipeline [21], with a bin size of $0.25° \times 0.25°$. Only events flagged as gamma rays and not recorded while the satellite crossed the South Atlantic Anomaly were accepted. We also rejected all events with reconstructed direction within 10° from the Earth limb, thus reducing contamination from Earth's gamma-ray albedo. W Com, observed at about 3 degrees off-axis with respect to the boresight, was only detected at the 3.7-σ level ($E >$ 100 MeV) from 12 (03:00 UT) to 13 (03:00 UT) June, 2008 with a flux of about 90×10^{-8} ph s^{-1} cm^{-2}, similar to the flux detected by EGRET [11]. In the rest of the observing period

[2]The average pedestal variations in digital counts [dc] describe the increased background light levels due to the moon. Values of 6.5 to 6.8 are typical for regular observations of extragalactic targets in moonless nights.

[3]The varying brightness levels due to moon are taken into account in the Monte Carlo simulations.

[4]see [4] for a discussion of systematic errors.

the source was not detected above 3σ; we report the measurement and upper limits (95% confidence level) in Table II and Figure 3. The paucity of photons prevents us from extracting a spectrum. SuperAGILE, the hard X-ray imager onboard AGILE (20-60 keV, [10]) observed the source for a net exposure time of 253 ks. The source position in the orthogonal SuperAGILE reference system was $\sim$ (3,0) deg, which means that almost the full on-axis effective area was exposed [10]. W Com was not detected, and we estimate a 3-σ upper limit in the 20-60 keV energy of 6 mCrab $\simeq 6.9 \times 10^{-11}$ erg cm^{-2} s^{-1}.

TABLE II
DETAILS AND RESULTS OF THE AGILE OBSERVATIONS OF W COM.

MJD	significance	flux or 2σ upper flux limits (E>100 MeV) [ph/cm^2/s]
54626.75 - 54629.12	$< 3\sigma$	$< 40 \times 10^{-8}$
54629.12 - 54630.12	3.7σ	$(90 \pm 34) \times 10^{-8}$
54630.12 - 54632.50	$< 3\sigma$	$< 37 \times 10^{-8}$

C. *Swift*

Observations of W Com with the *Swift* satellite were taken on June 8 and 9, 2008 (MJD 54625 and MJD 54626), respectively, and were partly contemporaneous with VERITAS and AGILE observations. Presented here are the data from the XRT [7] and UVOT [18] instruments. A standard data reduction was performed with the HEAsoft 6.5 package. All XRT observations were taken in Photon Counting (PC) mode. The count rate is above 0.5 cts/s during some observations and photon pileup occurred. For these observations an annular source extraction region was applied to exclude the central 3 pixels. See [4] for a detailed description of the *Swift* data analysis.

A large data set of optical and radio observations has been taken during the considered time period, but is not shown here; see [4] for more details.

III. DISCUSSION

Figure 3 shows the spectral energy distribution (SED) of W Com from UV to VHE gamma rays for three different time intervals: the large flare measured by VERITAS and *Swift* (June 7-8 2008; MJD 54624 - 54626), AGILE, VERITAS and *Swift* measurements with no significant signal above 100 MeV and 200 GeV (June 9 2008; MJD 54626-54627) and data taken by AGILE after MJD 54630 (June 12-15 2008).

We first note from Figures 2 and 3 presented here and Figures 3 and 4 in [1] that while the integral flux above 200 GeV is about 3 times higher for June 7-8 2008 than for March 2008, no change in the photon index is observed. We observe furthermore the approximately same flux and spectral index in X-rays on June 9 2008 as in March 2008; the short observation time with VERITAS on June 9 does not allow a detection of VHE gamma rays at a flux level similar to that observed in March 2008.

The SED of W Com can be fit by a one-zone, time dependent, combined synchrotron self-Compton (SSC) and external Compton (EC) jet model. The equilibrium version of the code of [6] has been used. In this model a population of ultrarelativistic nonthermal electrons and positrons is continuously injected into a spherical emitting volume of comoving radius R_b moving with a relativistic speed $\beta = (1 - 1/\Gamma^2)^{-1/2}$ along the jet. The spectrum of the injected pair population is specified through the injection power L_e and an unbroken power law with low- and high-energy cutoffs γ_{min} and γ_{max}, respectively, and a spectral index q. The injected particles suffer energy losses via synchrotron emission and upscattering of synchrotron or external photons or may escape from the emitting region. The particle escape is parameterized through an energy-independent timescale $t_{esc} = \eta R_B/c$, with $\eta \geq 1$. $\gamma\gamma$-absorption of VHE gamma rays on low-energy extragalactic background photons has been taken into account using the scenario described in [9]. It should be noted that not all parameters of the model are constrained by the available data, and subject to some rather arbitrary, unconstrained choices (like the Doppler factor and details of the external radiation field).

Some preliminary fit results from the SSC models (solid lines) and SSC+EC (dashed lines) are shown in Figure 3, for a detailed discussion of the different fit results see [4] . The parameters for the SSC model for the June 7-8 2008 observations are: $\gamma_{min} = 9 \times 10^3$, $\gamma_{max} = 2.5 \times 10^5$, $q = 2.55$, $L_e = 3.4 \times 10^{44}$ erg/s, a magnetic field strength of 0.24 G, a Doppler factor $\delta = 20$ and a size of the emission region of $R_B = 3 \times 10^{15}$ cm. The SSC model provides a reasonable fit, but requires a sub-equipartition magnetic field (equipartition parameter $\epsilon_B = 2.3 \times 10^{-3}$). This is similar to what was found in the SSC-modeling of the March 2008 data [1]. The non-detection of W Com at energies above 200 GeV on and after June 9 2008 leaves the model fits unconstrained and without unique solution. However, all models predict a significant change in the spectral index of the radiating electrons between high (June 7-8 2008) and low (June 9 2008) X-ray states, being much softer in the low state ($q = 2.55$ vs $q = 3.5$).

The SSC+EC model includes photons emitted from the disk as a steady-state blackbody radiation peaking in the near-infrared. The SED is well described by this model with a magnetic field close to equipartition ($\epsilon_B = 0.3$). Figure 3 shows for comparison the SSC+EC fit results to the March 2008 data. The SSC+EC model fit obtained in March 2008 exceeds the upper flux limit at 100 MeV from AGILE observations on June 7 2008, while it describes well the optical and X-ray data for this day (see dotted line in Figure 3).

The light crossing time $\tau = R_B/(c \times \delta)$ is with values between 90 and 300 min in all models (SSC and SSC+EC) consistent with variability timescales observed in X-rays and gamma rays from W Com and other VHE blazars.

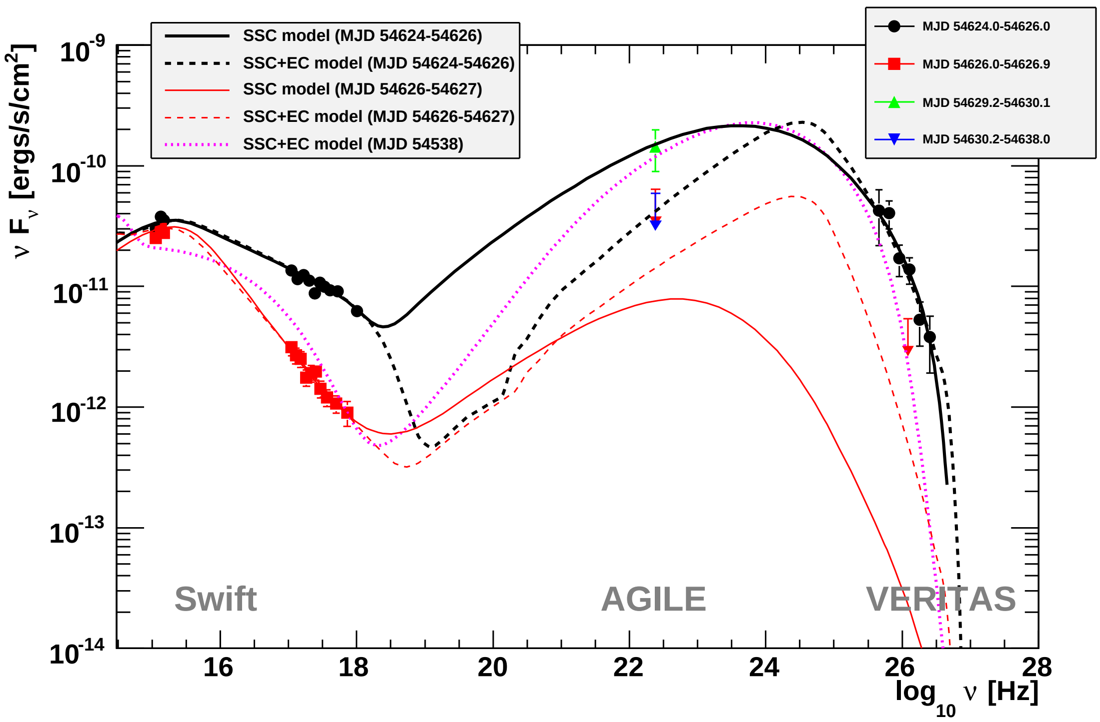

Fig. 3. Spectral energy distribution of W Com for MJD 54624 to 54638 including VERITAS, AGILE, and *Swift* XRT/UVOT data. Downwards pointing arrows indicate 2σ (AGILE data) or 3σ (VERITAS data) upper flux limits [12]. Details of the SSC and SSC+EC model fits are described in the text. The SSC+EC model fit to the March 2008 data (MJD 54538; see [1]) is indicated by a dotted line.

IV. Summary

The intermediate-frequency-peaked BL Lac object W Com was discovered during a strong outburst in March 2008. Here results from observations on June 7 and 8, 2008 of a second flare, with a three times higher flux of gamma rays above 200 GeV, are presented. The VERITAS observations were followed by radio, optical, UV and X-ray (*Swift*), and gamma ray (AGILE, $E >$100 MeV) observations. The SED can be modeled by a simple leptonic SSC model, but the wide separation of the SED peaks requires a rather low ratio of the magnetic field to electron energy density of $\epsilon_B = 2.3 \times 10^{-3}$. The SSC+EC model returns magnetic field parameters closer to equipartition, providing a satisfactory description of the broadband SED.

The strong variability of W Com at all energies on timescales of days or less shows that only truly contemporaneous data can provide serious constraints to the various emission models. The results presented here show that more data, especially in the hard X-ray to gamma-ray regime, is necessary to understand particle acceleration and high-energy gamma-ray emission in this interesting object.

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