Very High-Energy Gamma-Ray Emission from Markarian 501 as a Temporary EHBL During the July 2014 Flare

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Seminario de Física de Altas Energías

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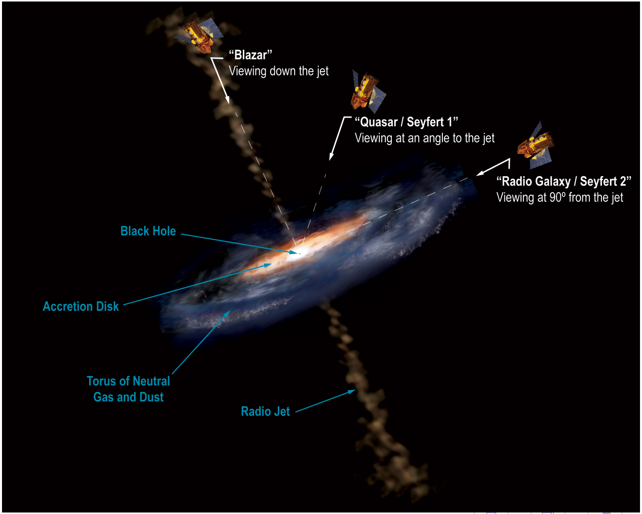
AGNs structure

- Relativistic jets
- Variability from minutes to years



Blazars definition

Blazars have energy around $10^{44} - 10^{48} erg/s$ and variability on timescales of hours to days.

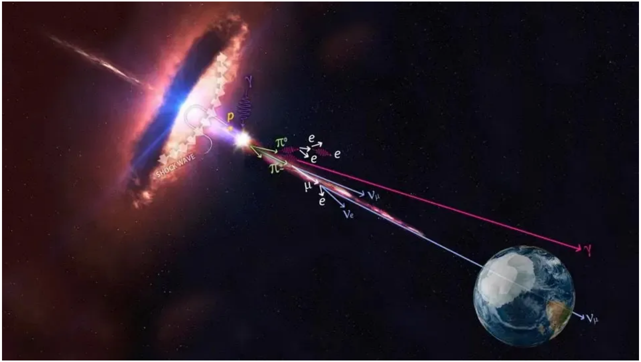


Figure: Active Galactic Nucleus pointing line of sight toward Earth.

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Blazars classification

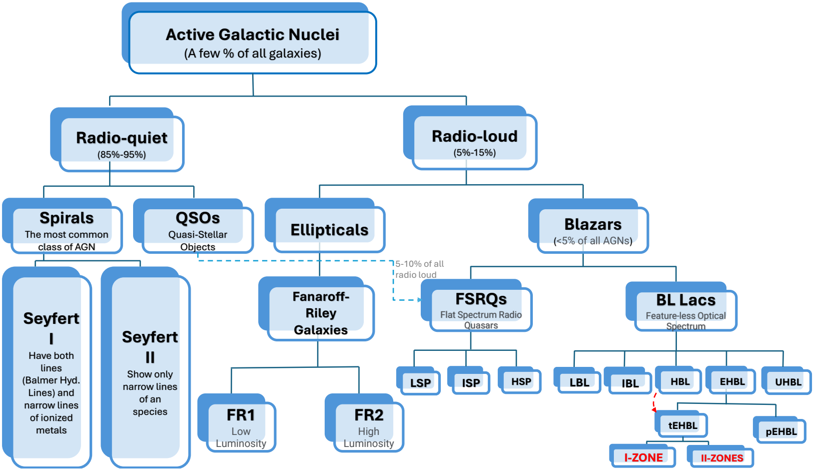

Figure: LBLs: $\nu_{peak} < 10^{14} Hz$, IBLs: $10^{14} Hz < \nu_{peak} < 10^{15} Hz$,HBLs: $10^{15} Hz < \nu_{peak} < 10^{17} Hz$, EHBLs: $\nu_{peak} > 10^{17} Hz$

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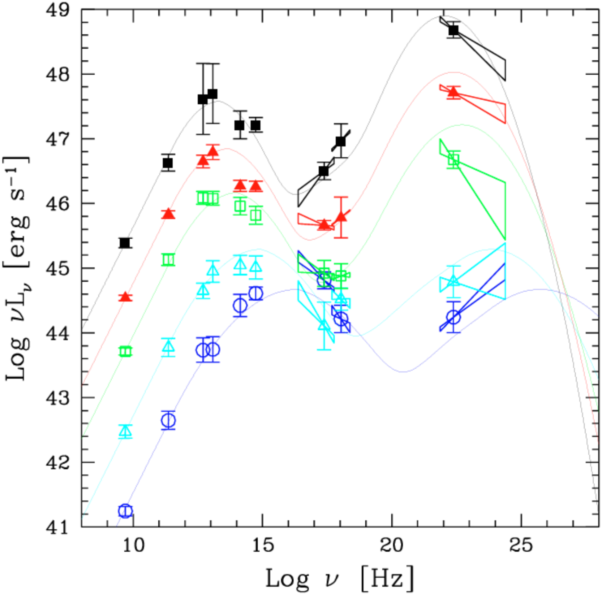
Spectral Energy Distribution



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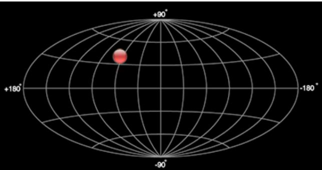
Blazars catalog

Markarian 501 SIMBAD

Canonical Name:	Markarian 501
TeVCat Name:	TeV J1653+397
Other Names:	4C +39.49 B3 1652+398 RGB J1653+397 H 1652+398 1ES 1652+398 3FGL J1653.9+3945 2HWC J1653+397 1LHAASO J1653+3943
Source Type:	HBL
R.A.:	16 53 52.2 (hh mm ss)
Dec.:	+39 45 37 (dd mm ss)
Gal Long:	63.60 (deg)
Gal Lat:	38.86 (deg)
Distance:	z=0.034
Flux:	(Crab Units)
Energy Threshold:	300 GeV
Spectral Index:	2.72
Extended:	No
Discovery Date:	1996-01
Discovered By:	Whipple
TeVCat SubCat:	Default Catalog
Source Notes:	



Observation Date (UT) 15-7-2025

Observation Lat ARGO-YBJ (30.11)

Vis-Plot this Source! Vis-Plot Full Year

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Major flaring events of Mrk 501

Year	Period	Instruments	Main characteristics
1996	–	Whipple	First detection of VHE γ rays ($E > 100$ GeV).
1997	Mar–Oct	Whipple, MWL	Flux up to 4 CU. Synchrotron peak > 100 keV (quiescent $\sim$1 keV). Magnetic field 0.07–0.6 G.
2005	May–Jul	MAGIC	Observed for 30 nights. VHE flux varied by $\sim 10\times$. On Jun 30/Jul 9, flux doubled in 2 min. Peaks shifted to higher energies.
2009	Mar–Aug	$\sim$25 inst.	Coordinated multiwavelength campaign.
2012	Mar–Jul	MAGIC, VERITAS, MWL	Flux > 0.2 TeV, peak on Jun 9. Very hard X-ray/VHE spectra. Synchrotron > 5 keV, SSC > 0.5 TeV. Classified as EHBL.
2012	Apr–May	TACTIC	> 850 GeV, 70 h exposure. From May 22–27, high flux up to 17 TeV.
2014	Jun 23–24	FACT, HESS	Extreme flare, comparable to 1997. Photons up to 20 TeV. Fast variability. Strongest flux seen by HESS.
2014	Jul 16–31	MAGIC, Swift-XRT	Multiwavelength flare. X-ray flux comparable to 1997. VHE flux (0.5–2 CU). On Jul 19, MAGIC detected a narrow feature at $\sim$3 TeV.

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Emission mechanism

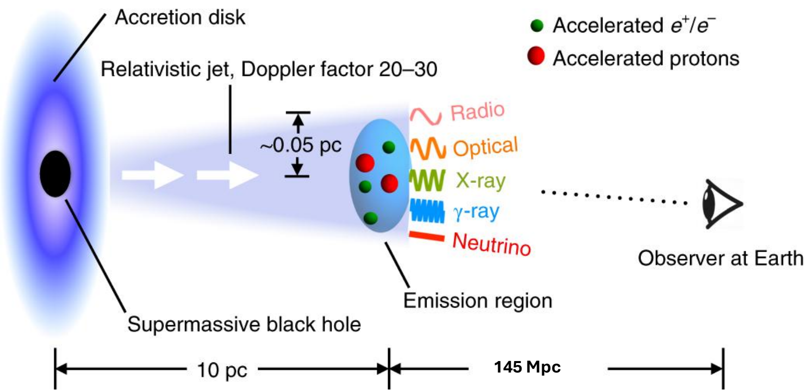

Figure: Taken from *Gao, S., Fedynitch, A., Winter, W. et al. Modelling the coincident observation of a high-energy neutrino and a bright blazar flare. Nat Astron 3, 88–92 (2019).*

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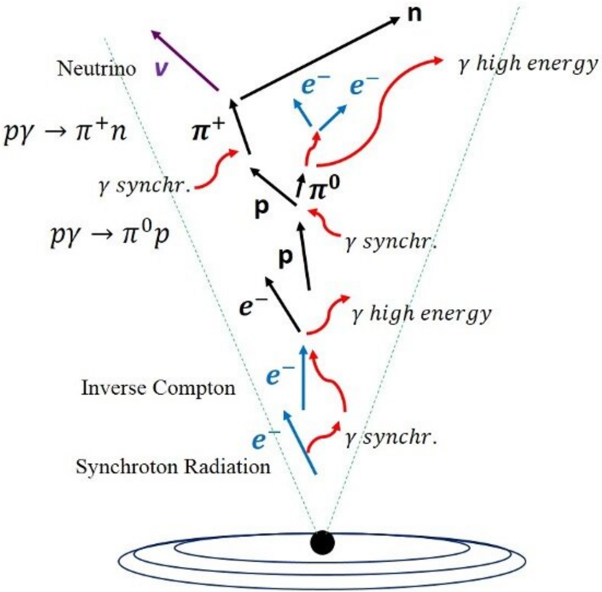
VHE γ-ray Emission



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Photohadronic interaction

Blob follows the Doppler factor $D = \Gamma^{-1}(1 - \beta \cos\theta_{\mathrm{ob}})^{-1}$.
With a power law

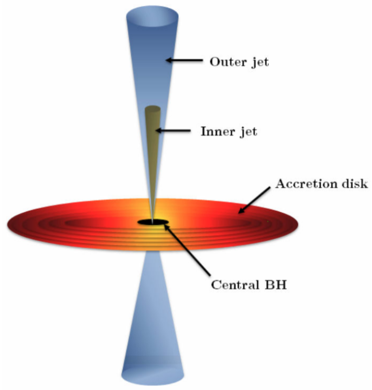
$$\frac{dN_p}{dE_p} \propto E_p^{-\alpha}, \tag{1}$$

to produce delta resonance Δ^+

$$p + \gamma \to \Delta^+ \to \begin{cases} p + \pi^0, & \text{fraction } \frac{2}{3}, \\ n + \pi^+, & \text{fraction } \frac{1}{3}, \end{cases} \tag{2}$$

$\pi^+ \to e^+ \nu_e \nu_\mu \bar{\nu}_\mu$ and $\pi^0 \to \gamma\gamma$.

Kinematical Conditions



Geometry of the flaring HBL.

$$\frac{n'_{\gamma,f}(\epsilon_{\gamma_1})}{n'_{\gamma,f}(\epsilon_{\gamma_2})} \approx \frac{n'_{\gamma}(\epsilon_{\gamma_1})}{n'_{\gamma}(\epsilon_{\gamma_2})}.$$

$$E_\gamma \epsilon_\gamma \approx 0.032 \frac{D\Gamma}{(1+z)^2}\,\mathrm{GeV}^2.$$

$$E_p \epsilon_\gamma \approx 0.32 \frac{\Gamma^2}{(1+z)^2}\mathrm{GeV}^2.$$

Extragalactic Bakground Light

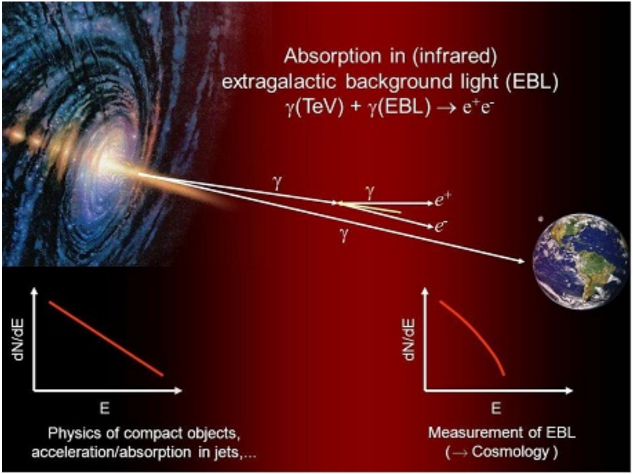


Figure: *HAGAR Group — A team for Ground TEV Gama Ray Astronomy. (s. f.). https://www.tifr.res.in/ hagar/results.php*

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Photohadronic model

$$F_\gamma(E_\gamma) \equiv E_\gamma^2 \frac{dN(E_\gamma)}{dE_\gamma} \propto E_p^2 \frac{dN(E_p)}{dE_p} n'_{\gamma,f}. \tag{3}$$

$$F_\gamma(E_\gamma) = F_{\text{int}}(E_\gamma) e^{-\tau_{\gamma\gamma}(E_\gamma, z)}. \tag{4}$$

$$F_{\text{obs}}(E_\gamma) = F_0 \left(\frac{E_\gamma}{\text{TeV}} \right)^{-\delta+3} e^{-\tau_{\gamma\gamma}(E_\gamma, z)}. \tag{5}$$

where

$$\delta = \alpha + \beta$$

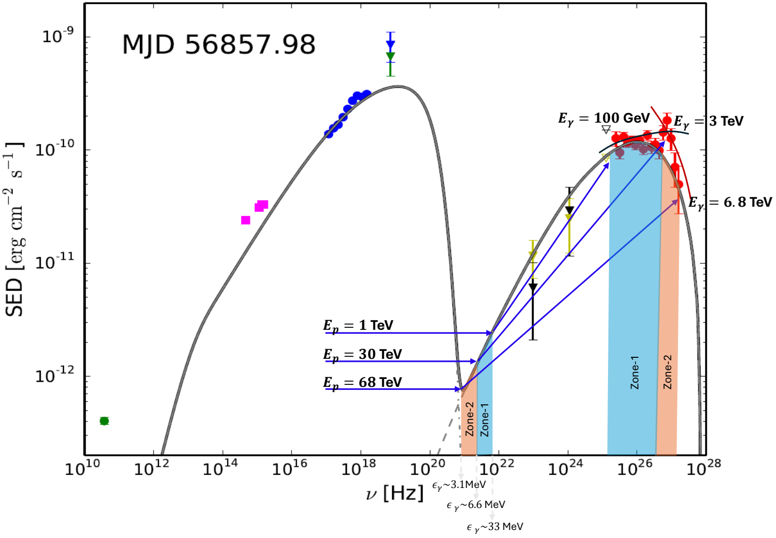

Figure: $\Phi_{SSC} \propto \epsilon^{\beta_1}$ in zone-1 and $\Phi_{SSC} \propto \epsilon^{\beta_2}$ in zone-2

2-zone Photohadronic model

For temporary extreme high-synchrotron-peaked BL Lacs (tEHBLs), a single power-law is insufficient. Instead, a two-power-law structure is assumed for the SSC component:

$$\Phi_{SSC} \propto \begin{cases} E_\gamma^{-\beta_1}, & 100 \text{ GeV} \lesssim E_\gamma \lesssim E_\gamma^c \\ E_\gamma^{-\beta_2}, & E_\gamma \gtrsim E_\gamma^c \end{cases} \tag{6}$$

where E_γ^c is the cutoff energy scale defining the transition between two spectral regions with spectral indices $\beta_1 \neq \beta_2$ ($\beta_i > 0$).
The observed flux is then modeled as:

$$F_{\gamma,\text{obs}} = e^{-\tau_{\gamma\gamma}} \times \begin{cases} F_1 \left(\frac{E_\gamma}{\text{TeV}}\right)^{-\delta_1+3}, & 100 \text{ GeV} \lesssim E_\gamma \lesssim E_\gamma^c \quad (\text{zone-1}) \\ F_2 \left(\frac{E_\gamma}{\text{TeV}}\right)^{-\delta_2+3}, & E_\gamma \gtrsim E_\gamma^c \quad (\text{zone-2}) \end{cases} \tag{7}$$

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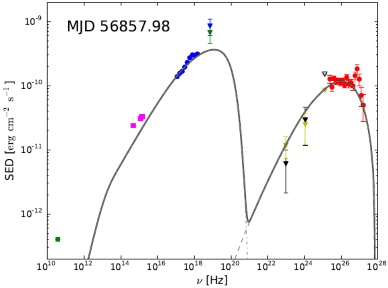
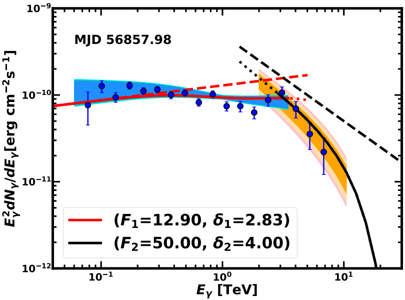
Results

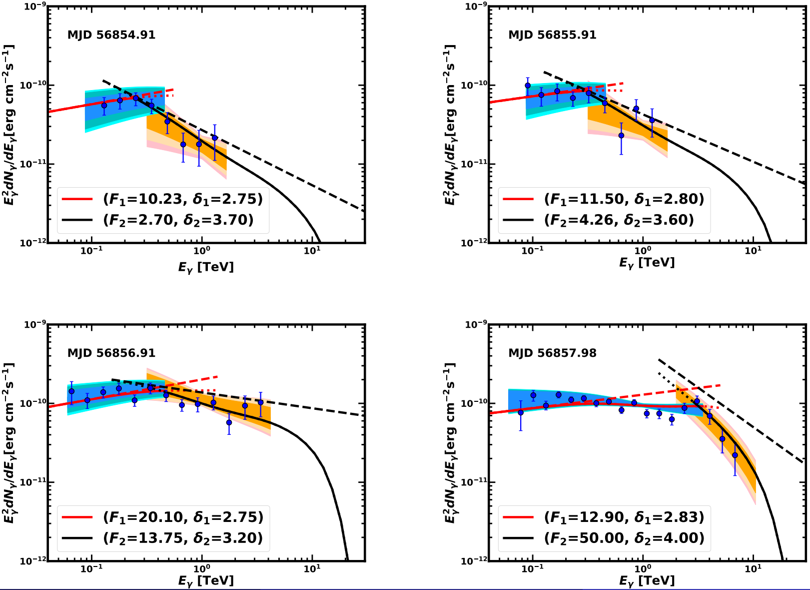
Mrk 501 was observed from July 16 to 31, 2014. MAGIC telescopes observed for 13.5 h under dark and good atmospheric conditions (MAGIC Collaboration et al. 2020).
MAGIC can detect air Cherenkov showers initiated by gamma rays in the energy range from ≈50 GeV to ≈50 TeV.



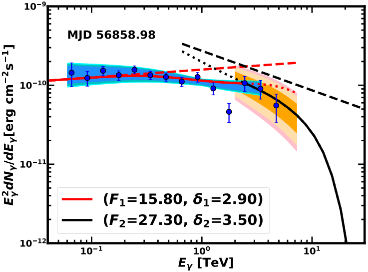


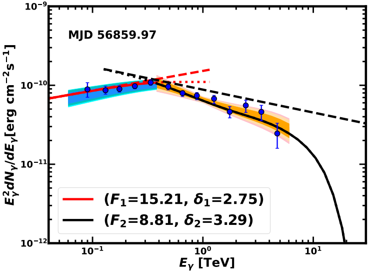
$$0.08\ \text{TeV} \leq E_\gamma \leq 6.8\text{TeV}.$$
$$E_\gamma^c = 3.18\ \text{TeV}.$$

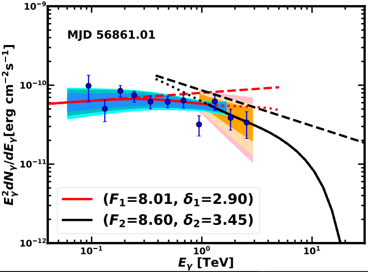
Day 1-4

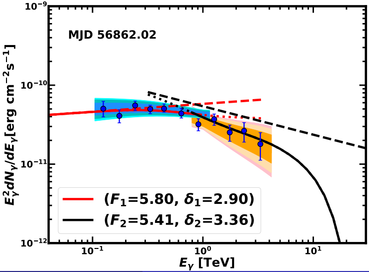

MJD 56854.91
$(F_1=10.23,\ \delta_1=2.75)$
$(F_2=2.70,\ \delta_2=3.70)$
MJD 56855.91
$(F_1=11.50,\ \delta_1=2.80)$
$(F_2=4.26,\ \delta_2=3.60)$
MJD 56856.91
$(F_1=20.10,\ \delta_1=2.75)$
$(F_2=13.75,\ \delta_2=3.20)$
MJD 56857.98
$(F_1=12.90,\ \delta_1=2.83)$
$(F_2=50.00,\ \delta_2=4.00)$
$E_\gamma^2 dN_\gamma/dE_\gamma$[erg cm^{-2}s^{-1}]
E_γ [TeV]

Day 5-8

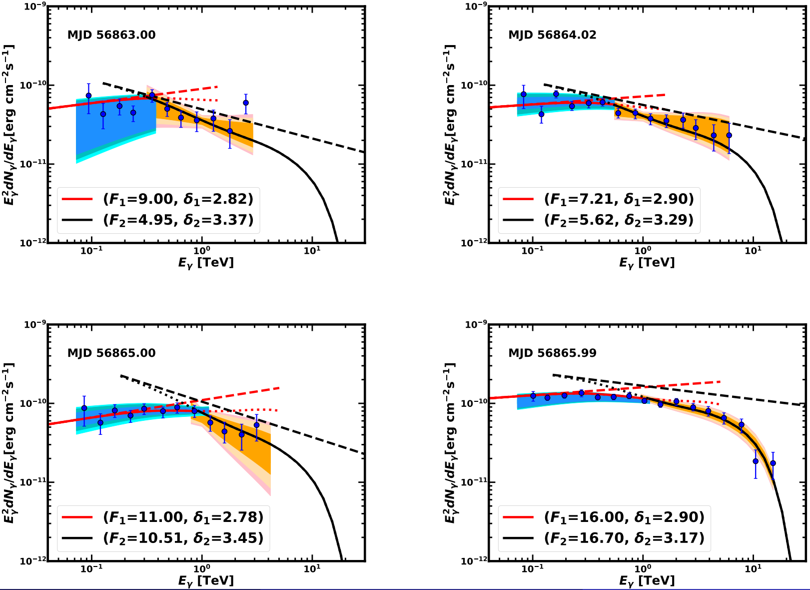

MJD 56858.98
$(F_1=15.80, \delta_1=2.90)$
$(F_2=27.30, \delta_2=3.50)$
$E_\gamma^2 dN_\gamma/dE_\gamma$[erg cm^{-2}s^{-1}]
E_γ [TeV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-1}
10^{0}
10^{1}


MJD 56859.97
$(F_1=15.21, \delta_1=2.75)$
$(F_2=8.81, \delta_2=3.29)$
$E_\gamma^2 dN_\gamma/dE_\gamma$[erg cm^{-2}s^{-1}]
E_γ [TeV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-1}
10^{0}
10^{1}

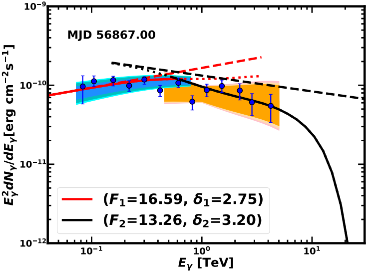

MJD 56861.01
$(F_1=8.01, \delta_1=2.90)$
$(F_2=8.60, \delta_2=3.45)$
$E_\gamma^2 dN_\gamma/dE_\gamma$[erg cm^{-2}s^{-1}]
E_γ [TeV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-1}
10^{0}
10^{1}


MJD 56862.02
$(F_1=5.80, \delta_1=2.90)$
$(F_2=5.41, \delta_2=3.36)$
$E_\gamma^2 dN_\gamma/dE_\gamma$[erg cm^{-2}s^{-1}]
E_γ [TeV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-1}
10^{0}
10^{1}

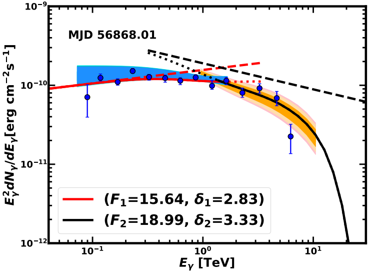
Day 9-12


MJD 56863.00
$(F_1=9.00, \delta_1=2.82)$
$(F_2=4.95, \delta_2=3.37)$
MJD 56864.02
$(F_1=7.21, \delta_1=2.90)$
$(F_2=5.62, \delta_2=3.29)$
MJD 56865.00
$(F_1=11.00, \delta_1=2.78)$
$(F_2=10.51, \delta_2=3.45)$
MJD 56865.99
$(F_1=16.00, \delta_1=2.90)$
$(F_2=16.70, \delta_2=3.17)$
$E_\gamma^2 dN_\gamma/dE_\gamma$[erg cm^{-2}s^{-1}]
E_γ [TeV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-1}
10^{0}
10^{1}

Day 13-15



MJD 56867.00
$(F_1=16.59,\ \delta_1=2.75)$
$(F_2=13.26,\ \delta_2=3.20)$
$E_\gamma^2 dN_\gamma/dE_\gamma$[erg cm^{-2}s^{-1}]
E_γ [TeV]



MJD 56868.01
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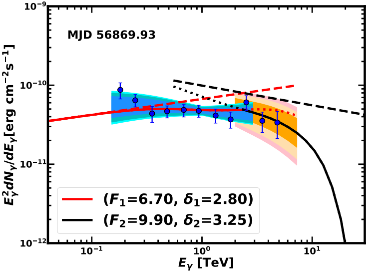
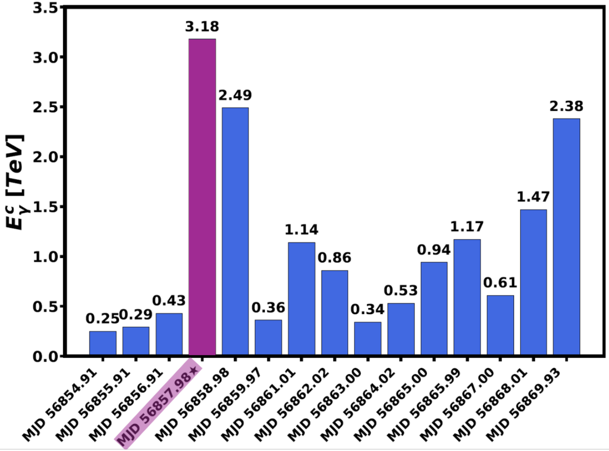
$(F_2=18.99,\ \delta_2=3.33)$
$E_\gamma^2 dN_\gamma/dE_\gamma$[erg cm^{-2}s^{-1}]
E_γ [TeV]



MJD 56869.93
$(F_1=6.70,\ \delta_1=2.80)$
$(F_2=9.90,\ \delta_2=3.25)$
$E_\gamma^2 dN_\gamma/dE_\gamma$[erg cm^{-2}s^{-1}]
E_γ [TeV]

Cutoff energy results



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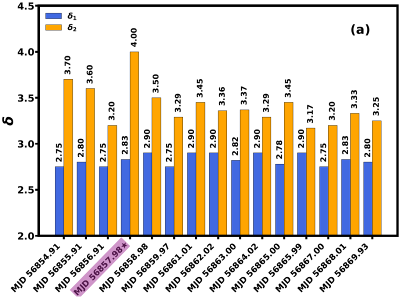
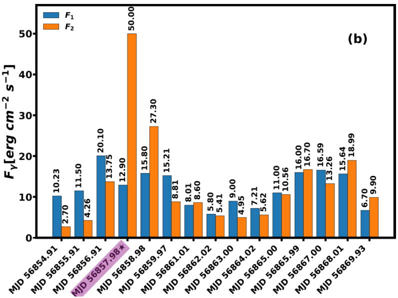
Intrinsic Flux and spectral index results





Conclusions and discussions

- When the synchrotron peak had shifted to frequencies above 10^{17} Hz, the VHE spectra were difficult to explain.
- Similar tEHBL-like behavior were also observed from Mrk 421 and 1ES 1959+650.
- It is observed that the spectra in zone-1 were like standard HBL ($2.5 \leq \delta_1 \leq 3.0$).
- Other nearby HBLs, which have already shown the temporary EHBL-like behavior in the past, may reincarnate again with vigor.

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