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AP Librae: The extended jet as the source of VHE emission?

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The LBL AP Librae is a fascinating blazar, since its spectrum contains several features, which are not easy to explain. First, the H.E.S.S. collaboration had announced the detection of VHE γ-ray emission from AP Librae. This implies an unusually broad inverse Compton component, since the X-rays are also inverse Compton dominated. Coupled with the narrow synchrotron component, the standard one-zone model fails to reproduce the spectrum. Secondly, X-ray emission from the extended jet has been detected, which closely follows the radio morphology. Due to the slope of the X-ray spectrum, one can conclude that the X-ray jet emission is of inverse Compton origin. Interestingly, an extrapolation of the Chandra jet spectrum to γ-ray energies intersects the Fermi-LAT spectrum exactly at the point of a strong break in the Fermi spectrum. This implies that the VHE spectrum measured by H.E.S.S. could be due to inverse Compton emission of the jet instead of the core.

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1. Introduction

BL Lac objects are a type of active galaxy, where the jet is closely aligned with the line-of-sight. They may be characterized by the peak position of their synchrotron component in the spectral energy distribution (SED). Low-energy peaked BL Lac objects (LBLs) exhibit the synchrotron maximum below 10^{14}Hz, while intermediate-energy peaked BL Lac objects peak between 10^{14}Hz and 10^{15}Hz, and high-energy peaked BL Lac objects contribute the most above 10^{15}Hz.

The blazar AP Librae, located at a redshift $z = 0.0486$ and at R.A. $= 15^h17^m41.8^s$, DEC. $= -24^\circ 22' 19.5''$, exhibits a monotonically increasing X-ray energy spectrum. In combination with the lack of optical emission lines it is classified as an LBL. However, some observational features of this source do not fit into this category.

Since LBLs exhibit their synchrotron peak frequency below 10^{14}Hz and the X-rays stem from the inverse Compton (IC) process, the maximum electron Lorentz factor in the electron energy distribution does not significantly exceed $\sim 10^4$ for reasonable values of the magnetic field strength on the order of ~ 0.1G. Hence, one would not expect very high energy γ-ray (VHE, $E > 100$GeV) emission from these objects. Surprisingly, AP Librae has been clearly detected by observations with the H.E.S.S. telescope array [5], and the SED extends to energies of a few TeV. Currently, AP Librae is the only LBL listed in the TeVCat[1], a catalog that gathers all sources detected above 100GeV. Despite selection biases, this makes AP Librae an exceptional source.

High resolution X-ray observations led to the detection of extended X-ray jets in many AGN. However, due to the small viewing angle, it is surprising to observe extended X-ray emission in blazars. An extended X-ray jet has been detected in AP Librae by [6], which has thus become one of only six BL Lac objects listed in the X-JET database.[2] Of these six objects three are synchrotron dominated, while the other three, including AP Librae, are IC dominated. Within the IC dominated objects, AP Librae has the lowest luminosity. The X-ray morphology of AP Librae's jet follows exactly the radio morphology as observed with the VLA. The detection of the extended X-ray jet further demonstrates AP Librae's peculiar state.

The detection in VHE implies an extremely broad high energetic component spanning 10 orders of magnitude of energy in the SED. Due to the required cut-off of the synchrotron emission below the X-rays, the broad high energetic component cannot be explained in the usual one-zone blazar model.

In this proceeding, we summarize our recent results [11] that the extended jet dominates the total SED in the VHE γ-ray regime. In fact, our model explains the VHE emission as originating mostly from the extended jet.

2. Important observations

We describe only the important observations, which are necessary for our jet model. The remaining multiwavelength data is taken from the following papers or publicly available data bases: Radio [7, 10], and IR/optical/UV [6, 4].

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[1] http://tevcat.uchicago.edu/

[2] `http://hea-www.cfa.harvard.edu/XJET/`

2.1 Radio

2.1.1 VLA

VLA observations [2] at 1.36GHz led to the detection of the extended jet on arcsec-scales emerging in a south-westerly direction. After ~ 12arcsec the jet bends to the north-west for another $\sim 10-20$arcsec.

2.1.2 MOJAVE

The MOJAVE program [8] utilizes VLBI radio observations at 15GHz to monitor blazars on milli-arcsec scales over long time periods. AP Librae was observed in this program over the course of ~ 15 years. The data set reveals a steady core component ("component 0"), which is weakly variable (flux within a factor of 2). Its flux is marked with the open diamond in Fig. 1.

Furthermore, a continuous jet is measured on scales of ~ 10milli-arcsec, which emerges in a southerly direction. Beyond this scales only knots are detected in a south-westerly direction, which is the same direction as the VLA jet on arcsec scales. The total flux measured in the MOJAVE observations fits with the other, unresolved radio data (c.f. Fig. 1).

The movement of some knots led to the determination of a maximum apparent speed of the jet of $6.8c$.

2.2 X-rays

Chandra observations revealed the extended jet on arcsec scales [6]. The photon index of the jet is $\Gamma = 1.8 \pm 0.1$, a hard spectrum indicating an IC dominance.

The Chandra spectrum of the core on arcsec scales is also hard with $\Gamma = 1.58 \pm 0.04$.

A 100-month average of observations with the Swift-BAT instrument [9] reveals a flux level of the hard X-rays that is in straight continuation of the Chandra core spectrum. Thus, the X-ray spectrum can be described by a single power-law over more than 2 orders of magnitude in energy.

2.3 γ-rays

Due to a lack of spatial resolution of the γ-ray instruments, the jet cannot be resolved. Data from Fermi and H.E.S.S. are taken from [5]. The γ-ray SED can be described by a flat level below a few GeV, followed by a power-law up to a few TeV.

3. The jet model

The data together with the modeling is presented in Fig. 1. The respective parameter sets are given in Tab. 1.

Blazars are commonly described by a one-zone model, which in most cases gives successful fits to the SED. This model fails for AP Librae. The most important constraint comes from the hard X-ray spectrum. Attributing the X-ray core data to synchrotron-self Compton (SSC) emission requires a high minimum electron Lorentz factor of $\sim 10^2$, because only below the photon energy associated with this electron energy the SSC spectrum is a pure power-law. Above this energy the SSC spectrum is significantly curved due to the convolution of the broken electron distribution with the synchrotron spectrum and the complicated IC cross section. Thus, no good fit is possible of

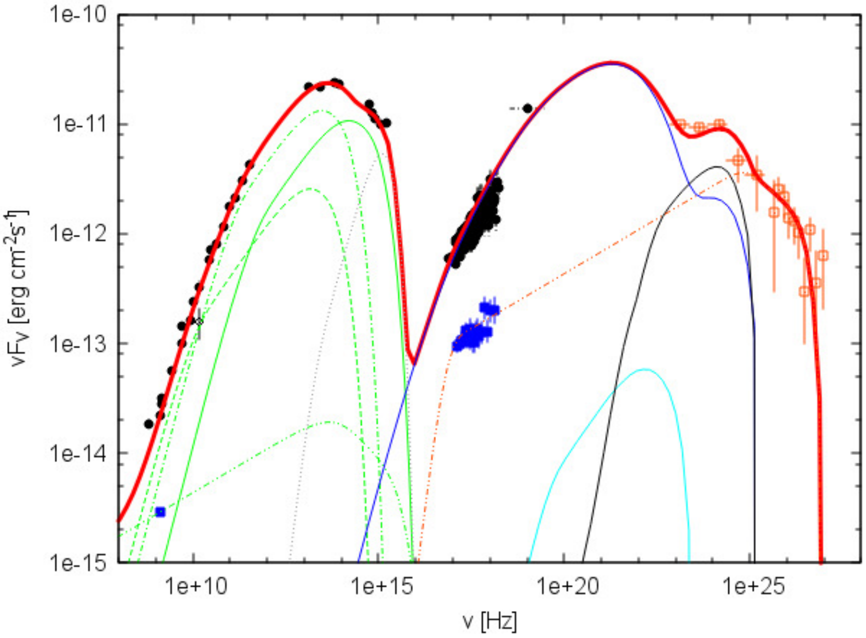

Figure 1: SED of AP Librae with the modeling of the blob and the jet. The data points are for the kpc-core (black dots), the jet on kpc-scales (blue squares), the steady component of the MOJAVE observation (open diamond), and the γ-ray data (red squares) where the jet cannot be resolved. The line styles refer to the blob (solid), the "small jet" (dashed), the "pc-jet" (dash-dotted), and the jet on kpc-scales (dash-double-dotted). The line colors imply synchrotron (green), accretion disk (dotted gray), SSC (blue), IC/Disk (cyan), IC/BLR (black), and IC/CMB (red) emission. The thick red line is the sum of all radiative components.

	Component 0		pc-jet	kpc-scale jet
	blob	small jet		
n_e [cm^{-3}]	8.5×10^{3}	6.2×10^{-6}	3.0×10^{-7}	1.8×10^{-10}
γ_{min}	1.5×10^{2}	1.0×10^{2}	5.0×10^{2}	6.0×10^{1}
γ_{br}	2.6×10^{3}	3.8×10^{3}	7.7×10^{3}	6.7×10^{5}
γ_{max}	8.0×10^{3}	1.0×10^{4}	2.0×10^{4}	5.0×10^{6}
s_1	2.0	2.0	2.0	2.6
s_2	3.0	3.0	3.0	3.6
B_0 [G]	0.2	0.01	5.0×10^{-3}	2.5×10^{-6}
Γ_b	10	10	10	10
R [cm]	1.0×10^{15}	1.5×10^{18}	3.0×10^{18}	3.0×10^{21}
ϑ_{obs} [deg]	2.0	2.0	2.0	4.0
l'_{jet} [pc]	-	1.0	10.0	1.0×10^{4}
N_{jet}	1	42	214	107

Table 1: Parameters for the fit. n_e is the electron density; γ_{min}, γ_{br} and γ_{max} are the minimum, break and maximum electron Lorentz factor, respectively; s_1 and s_2 are the electron spectral index before and after the break, respectively; B_0 is the magnetic field strength; Γ_b is the bulk Lorentz factor; R is the radius of the components; ϑ_{obs} is the observation angle; l'_{jet} is the projected jet length; N_{jet} is the number of zones in each component.

the Chandra and the Swift-BAT spectrum if the minimum Lorentz factor is set below 10^2. Another constraint comes from the fact that the Swift-BAT flux is slightly above the flux level of the γ-ray flux below a few GeV. Hence, the maximum of the IC component must be located between 100keV and 100MeV resulting in a maximum electron Lorentz factor below $\sim 10^4$.

In turn, the electron distribution function, which explains the X-ray core data, is very narrow, and cannot account for either the synchrotron emission below the optical band nor for the VHE γ-ray emission. The resulting model is presented with solid lines in Fig. 1. The fit is good in the optical regime. The flattening of the Swift-UVOT spectrum at higher UV energies suggest the addition of another component, which is usually attributed to the accretion disk. The accretion disk can illuminate the gas in close proximity of the black hole, which would lead to a (low-luminous) broad-line region. These two photon fields can serve as target photons for IC scattering by the blob electrons. The resulting flux at high energies is plotted in Fig. 1 as cyan (IC/Disk) and black (IC/BLR). The former does not contribute significantly to the overall emission, while the latter can explain the missing flux below a few GeV. However, due to the low maximum electron Lorentz factor, these emission processes cannot explain the VHE emission, either.

Furthermore, the synchrotron component below the optical regime cannot be modeled by the blob emission. Especially, the flux of "component 0" is not fitted at all.

In order to explain the rest of the SED, we thus invoke the jet as a whole. It is modeled as the combination of a number of self-similar single zones. The combined emission of all zones gives the total flux of the jet.

Due to different observational constraints, we separate the jet into three parts. The outer part models the jet on kpc-scales, where it is detected in the VLA and Chandra data. Since the flux in both radio and X-rays drops beyond the bend [6], we only consider the part closer than $\sim$ 12arcsec from the core corresponding to a projected length of roughly 10kpc. The "pc-jet" takes into account the extended emission in the MOJAVE data set on scales of a few milli-arcsecs, which corresponds to a jet length of about 10pc (projected). The inner jet (the "small jet") has a projected length of 1pc (which corresponds to the MOJAVE resolution limit) and is considered, because the emission on these scales is influenced by both the blob and the thin jet medium. The inner jet is constrained by the fact that it should fit the flux of "component 0", while the combined flux of the "small jet" and the "pc-jet" should not exceed the total radio emission. The 15GHz measurement is the total flux of the MOJAVE observations including both the "component 0" and the extended milli-arcsec emission.[3] Hence, the data at other radio frequencies is influenced by both the "small jet" and the "pc-jet". Due to the low electron densities in the extended components, the IC flux is in most cases below the scales displayed in Fig. 1.

The "small jet" and the "pc-jet" in combination with the blob explain very well the total synchrotron emission. The data of the kpc-scale jet is modeled with synchrotron and IC/CMB emission, which gives a nice fit in the radio and the Chandra energy range. Interestingly, the extrapolation of the Chandra jet spectrum intersects the Fermi data roughly at the break at a few GeV. This led us to the hypothesis that the VHE emission could originate in the kpc-scale jet. In fact, by choosing a maximum electron Lorentz factor of $\sim 5 \times 10^6$ in the kpc-jet, we successfully reproduced the VHE spectrum.

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[3] The flux value given is the average over all MOJAVE observations.

4. Discussion & Conclusions

As was shown in the previous section, the extended jet plays an important role in the radiative output of AP Librae. It is responsible for a significant part of the SED.

Most importantly, the jet could be responsible for the VHE emission detected with the H.E.S.S. telescopes. This is an unusual interpretation, since it implies highly relativistic flows and continuous reacceleration of the jet material on very large scales (AP Librae's jet is modeled with a deprojected length of 140kpc). Below we present a few suggestions how to test this theory.

Due to the required highly relativistic electrons, the jet should emit synchrotron emission up to the UV band. Since the contribution of the galaxy in the UV band is much reduced compared to the optical and IR bands, the jet should be detectable despite its proximity to the bright core. If the jet is not detected in the UV with an upper limit below the predicted flux of our model curve, the IC/CMB is ruled out as the origin of the VHE emission, because the required electron energies cannot be matched.

In the kpc-scale jet the relative flux decrease along the jet is expected to differ between the synchrotron and IC domains due to different beaming dependencies [3]. More sensitive mapping at radio and X-ray frequencies could test this prediction.

Additionally, the HE and VHE emission can also be used to indirectly test the model. We do not expect variability in the extended jet emission, because such a large object requires to be steady over time scales much longer than a few times l_{jet}/c. Thus, the flux above a few GeV should not drop below the average level. An increase in the flux at these energies during a flare might still originate from an additional flaring component and would not rule out the above model. However, this component should also change the spectrum in the UV and potentially in the X-ray band.

Hence, more observations in basically all energy bands are strongly encouraged.

If confirmed, the emission of TeV radiation by an extended, more than 100kpc long jet would be a major result with strong implications for the transport and acceleration processes on large spatial scales.

Acknowledgments

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