DISCOVERY OF AN EXTENDED X-RAY JET IN AP LIBRAE

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ABSTRACT

Chandra observations of the low-energy-peaked BL Lac object (LBL) AP Librae (AP Lib) revealed the clear discovery of a non-thermal X-ray jet. AP Lib is the first LBL with an extended non-thermal X-ray jet that shows emission into the very high energy range. The X-ray jet has an extension of ≈15'' (≈14 kpc). The X-ray jet morphology is similar to the radio jet observed with Very Large Array at 1.36 GHz emerging in the southeast direction and bends by 50° at a distance of 12'' toward the northeast. The intensity profiles of the X-ray emission studied are consistent with those found in the radio range. The spectral analysis reveals that the X-ray spectra of the core and jet region are both inverse-Compton (IC)-dominated. This adds to a still small sample of BL Lac objects whose X-ray jets are IC-dominated and thus more similar to the high-luminosity Fanaroff–Riley II sources than to the low-luminosity Fanaroff–Riley I objects, which are usually considered to be the parent population of BL Lac objects.

Key words: BL Lacertae objects: individual (AP Lib) – galaxies: active – galaxies: jets – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

The low-energy-peaked BL Lac object (LBL) AP Librae (AP Lib, PKS 1514−241) has a redshift of z = 0.0486 (Disney et al. 1974) and is located at α2000 = 15h17m41.8s ± 0.00002, δ2000 = −24°22′19.4759″ ± 0.0003 as determined from very long baseline interferometry (VLBI) observations by Lambert & Gontier (2009). It has been classified as a BL Lac object by Strittmatter et al. (1972) and Bond (1973).

AP Lib is well known as one of the most active blazars in the optical band. In data from 1989, intra-day variability was detected with a very high rate of change of 0.06±0.01 mag hr−1 (Carini et al. 1991). Even on shorter timescales of 20 minutes, variations of up to 0.5 mag were detected in 1973 (Miller et al. 1974).

AP Lib was historically classified as a so-called radio-selected BL Lac objects. In the 1990s, BL Lac objects were found mainly in radio or X-ray surveys and therefore were classified as radio- or X-ray-selected BL Lac objects. The spectral energy distributions (SED) of BL Lac objects show two prominent peaks that are commonly described in a lepton model as synchrotron and inverse Compton (IC) emission, respectively. The peak energy of the low-energy (synchrotron) component is used to classify BL Lac objects as LBL and high-energy-peaked (HBL), with occasional references to a group of intermediate-energy-peaked BL Lac objects (IBL). This classification is frequently based on the slope of the X-ray spectrum. Ciliegi et al. (1995) found that the X-ray spectrum of AP Lib can be described by a power law with a photon index of 1.5−1.7. AP Lib is thus classified as LBL and it is assumed that the X-ray emission of the core is due to IC scattering of the synchrotron emission, and, possibly, external radiation. The peak energy of the gamma-ray component of LBL objects is expected to arise in the keV–GeV range and therefore a rather low flux in the TeV γ-ray range is expected (close to or below the detection limit of current Cherenkov telescopes). Hence, it is rather unexpected to detect very high energy (VHE, E > 100 GeV) γ-ray emission from an LBL. Therefore it was remarkable that in 2010 June/July, VHE γ-ray emission was detected from the position of AP Lib (Hofmann 2010).

The standard picture of active galactic nuclei (AGN; e.g., Blandford & Rees 1974) explains the different observational characteristics of AGN with the orientation of the jet axis to the line of sight to the observer. BL Lac objects are interpreted as aligned (beamed) versions of Fanaroff–Riley I (FRI; Fanaroff & Riley 1974) radio galaxies while steep spectrum radio quasars (FSRQ) are aligned versions of Fanaroff–Riley II (FRII) galaxies. BL Lac objects are known to have very energetic jets pointing under small viewing angles toward the observer.

Radio observations of AP Lib at 1.4 GHz reveal the detection of one-sided, diffuse radio emission at the arcminute scale (Condon et al. 1998). Observations with the Very Large Array (VLA) at 1.36 GHz and 4.6 GHz result in the detection of a one-sided radio jet emerging to the southeast direction and bending toward northeast at ~12 arcsec distance from the core (Cassaro et al. 1999). Very Long Baseline Array (VLBA) observations detected the radio jet at milliarcsecond scale which emerges to the south (MOJAVE3; Lister et al. 2009).

The inhomogeneous collection of published X-ray jets (status 2013 March: 113 X-ray jets), the XJET database,4 contains 77% high-luminosity sources (FRII, quasars) and ~23% low-luminosity sources (20 FRI, 5 BL Lac objects, and 1 Seyfert 1 galaxy). The X-ray emission detected from the jets of FRII sources are dominated by synchrotron emission (Harris & Krawczynski 2006). Most high-luminosity sources (quasars, FRII) have X-ray jets with flat (α < 1) spectra, suggesting this part of the spectrum to be dominated by IC emission (e.g., Harris & Krawczynski 2006; Worrall 2009). While IC scattering of cosmic microwave background (CMB) photons is an explanation for flat X-ray spectra preferred by many, problems with this interpretation have been discussed by Harris & Krawczynski (2006) and Worrall (2009).

3 http://www.physics.purdue.edu/MOJAVE/
4 http://hea-www.harvard.edu/XJET/
Figure 1. X-ray count map of AP Lib from 0.2 to 8 keV extracted from the 12.8 ks observation by Chandra. The jet is clearly visible. Due to the subarray used, the observed frame is cut at the left part of the image, indicated by the line. (A color version of this figure is available in the online journal.)

Among the sources in this database, only the radio galaxies Cen A and M87 and the FSRQ PKS 1222+216 and PKS 1510+089 have been traced up to TeV energies. AP Lib is the first BL Lac object with an extended X-ray jet that has been detected in the TeV energy range.

The luminosity distance of AP Lib, using \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), is \( d_L = 210 \) Mpc. The scale is 1\arcsec\ = 0.95 kpc.

2. EXTENDED X-RAY JET

X-ray observations of AP Lib were analyzed to search for high-energy emission of the one-sided radio jet. The source was observed with Chandra on 2003 July 4 (ObsID: 3971) with an exposure of 12.8 ks. The data were taken in timed exposure mode using a subarray of one-eighth of the chip (128 rows). This mode decreases the frame time to 0.4 s and reduces pileup. The data were recalibrated using the calibration database CALDB. The Chandra data have been analyzed with the software CIAO v4.1.

A clear X-ray jet was detected (Kaufmann et al. 2011) in this Chandra observation (see Figure 1). The jet extends toward the southeast direction of AP Lib. Unfortunately, the exposure is rather low, so that the real extension of the jet cannot be measured.

Despite the timed exposure mode, the brightness of the core causes a faint “readout artifact” visible in the column in which the bright core region is located. For the spectral analysis, the signal of the influenced columns is replaced by a typical background level to correct for this artifact. The tool acisreadcorr has been used to correct the data. For the subarray used, the BACKSCAL header keyword had to be modified.

As can be seen in Figure 1, the X-ray jet emerges in the southeast direction up to an extension of \( \sim 12\arcsec \) and bends with an angle of \( \approx 50^\circ \) to the northeast. The jet broadens toward the outer regions and becomes fainter.

In order to compare the morphology of the X-ray jet to the radio jet studied with VLA by Cassaro et al. (1999), the X-ray count map has been smoothed (see Figure 2) with an elliptical Gaussian with a major axis 3\arcsec\ and a minor axis 2\arcsec\ using the tool fgauss. The shape for the elliptical Gaussian matches the beam profile of the VLA data. The VLA radio contours (described in

http://cxc.harvard.edu/ciao/threads/acisreadcorr/index.html#subarray

Figure 2. X-ray count map of the energy 0.2–8 keV with adaptive smoothing using an elliptical Gaussian. The X-ray jet is clearly visible. Contours of the VLA observation of AP Lib in A+B configuration at 1.36 GHz and the restoring beam in the position angle (P.A.) 28\(^\circ\) are taken from Cassaro et al. (1999). (A color version of this figure is available in the online journal.)
Section 3.1.1) are overlaid onto the smoothed X-ray map (see Figure 2). The jets in the radio and X-ray bands have very similar morphologies. They extend in the same direction, bend at the same distance by the same amount, and have comparable spatial profiles. Neither the X-ray nor the radio jet displays knots, hotspots, or other features of high contrast. No feature on the counterjet side could be detected in either band. A quantitative comparison is presented in Section 2.1.

2.1. Intensity Profiles

Radial profiles have been extracted with the tool dmextract from the whole source (core and jet) using 20 equidistant circular annuli of width \( \sim 1'' \). In addition, a fraction of the annuli ( wedge ) with opening angle 100° in the direction of the jet has been used. A circular region close to the source in northwest direction with radius \( \sim 9'' \) was used to determine the background for the radial profile.

The two methods (complete annuli and a fraction of the annuli) used to obtain the radial profile do not show significant differences. This radial profile and its comparison to the point spread function (PSF) are used to identify the extension of the jet and to find the best regions to obtain the core and jet spectra.

The radial profiles have been extracted for two different energy sub-bands (0.2–1.5 keV (S) and 1.5–8 keV (H)) and the hardness ratio profile has been calculated to study the spectral trends in the jet region. The hardness ratio profile has no significant trend within 15''.

The PSF for the specific on-axis angle of the source was derived using the Chandra Ray Tracer (ChaRT) which simulates the High Resolution Mirror Assembly based on an input energy spectrum of the core and the exposure of the observation. The output from ChaRT can be modeled, taking into account instrument effects of the various detectors, using the software MARX to obtain the image of the simulated PSF on the detector. The radial profile for this PSF has been created with wedge annuli with an opening angle of 100°.

The radial profile of the X-ray source deviates significantly from the PSF at radii >2'' (see Figure 3). The jet at radii >3'' has a linear structure and therefore the intensity profile for the jet has been created using rectangular regions along the jet.

The intensity profile of the X-ray and radio jet has been extracted by integrating the counts at equidistant steps of 1.5'' along the jet and perpendicular to the direction of the jet to compare the X-ray and radio morphology of the jet (see Figure 4). In order to account for the jet bend, profiles along and across the jet are determined from 3'' to 13.5'' along P.A. = 120° and from 13.5'' to 22.5'' along P.A. = 70°. In order to avoid contributions from the core, a minimum distance of 3'' was chosen. As can be seen in Figure 4, the same morphology is detected of the X-ray and radio emission with a slightly shallower gradient of radio flux in the outer region of the jet.

The transversal profile (see Figure 4) of the jet from 3'' up to 13.5'' (\( \sim 2.9''–12.8\) kpc) was determined along P.A. = 120°. The transversal profile of the X-ray and radio emission is comparable and the jet width is 5'' \( \sim 4.8\) kpc in both energy bands.

The profiles of both energy bands are compatible. This suggests that the same particles are responsible for the radio and X-ray jet.

2.2. Spectra

The spectra of the core and the jet of AP Lib and of a background region are determined with the tool dmextract. The response files are obtained with the tool asphist and the ARF are created using asresponse

The X-ray spectrum of the core was extracted using a circular region with radius 3''. The background spectrum was determined within a region of radius 25'' close to the source in the north direction. To obtain the spectrum of the extended emission, a circular region with radius 15'' was used in which the region around the core was excluded (see Figure 5). As can be seen from the radial profile, the core exclusion region is large enough to avoid any influence of the core photons. Based on the radial profile of the core and jet (Figure 3) and the shown PSF, the wing of the PSF of the core contributes \(<10\%\) to the jet spectrum obtained in the range >3''.

The X-ray spectra have been binned with the tool grppha to obtain at least 25 counts per bin to reach the necessary significance for the \( \chi^2 \) statistics. The program xspec v12 was used to fit the X-ray spectra in the energy range 0.2–8 keV. The uncertainties on the model parameters are given as confidence intervals. The fit parameter is changed by \( \Delta \chi^2 = 2.71 \). This represents the 90% confidence interval.

The spectrum of the core can be well \( \chi^2 / \text{dof} = 165/147 \) described by a power law of the form \( N(\varepsilon) = N_0 \times \varepsilon^{-\Gamma} \) with \( \Gamma = 1.58 \pm 0.04 \) taking into account the Galactic absorption of \( N_H = 8.36 \times 10^{20} \) cm\(^{-2} \) (LAB survey; Kalberla et al. 2005). The resulting flux is \( F_{\text{core,2--10keV}} = (2.9 \pm 0.1) \times 10^{-12} \) erg cm\(^{-2} \) s\(^{-1} \). Although no hints for pileup appear in the residuals of the power-law fit, a test for pileup has been performed. Therefore, the spectrum of the core region has been extracted from an annulus region of the same size, in which the innermost pixels (inner radius of \( \sim 1'' \)) are excluded. The spectral slope of the determined spectrum (\( \Gamma = 1.6 \pm 0.1 \)) is comparable to the core spectrum of the circular region and therefore no pileup was detected.

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8 http://space.mit.edu/CXC/MARX/
7 http://space.mit.edu/CXC/MARX/
Figure 4. Left: jet intensity profile of the X-ray (circles) and radio emission (dashed line) from box regions along the jet. The brightness has been normalized to the first value with a surface brightness of 5.2 counts arcsec\(^{-2}\) for the X-ray emission and 16.15 mJy beam\(^{-1}\) for the radio emission. The dotted vertical line indicates the region of the bending of the jet. Right: transverse jet profile of the X-ray emission shown as circles and the radio emission indicated as dashed line. The brightness has been normalized to the highest value with a surface brightness of 7.6 counts arcsec\(^{-2}\) for the X-ray emission and 26. mJy beam\(^{-1}\) for the radio emission.

Figure 5. X-ray count map of the Chandra observation with the different regions used for the spectral analysis of the jet.

To quantify and to search for spectral differences, three different regions have been used, as illustrated in Figure 5. The extended emission region is a circular region with a radius 15\(\arcsec\) excluding the core region with a radius 3\(\arcsec\). The wide jet region is a wedge region with a radius 20\(\arcsec\) with an opening angle of 100\(^\circ\) along the jet and the inner jet region is a wedge region with an opening angle of 30\(^\circ\) and a radius of 10\(\arcsec\).

The spectrum of the jet obtained from the extended emission region can be described by \(\Gamma = 1.8 \pm 0.1\) taking into account the Galactic absorption \(\chi^2/\text{dof} = 13/18\). The resulting flux is \(F_{\text{jet,2-10}\text{keV}} = (2.3 \pm 0.3) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\).

The spectrum from the wide jet region can be fit with a photon index of \(\Gamma = 1.8 \pm 0.2\) \((\chi^2/\text{dof} = 6/13)\) comparable to the one above. The resulting flux is \((1.6 \pm 0.3) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\). An even smaller region, the inner jet region, was used to determine the spectrum of the inner parts of the jet. Since the region is very small, the spectrum consist of only a few photons, and therefore a reduced flux of \((6.0 \pm 1.7) \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}\) resulted. The slope \(\Gamma = 1.9 \pm 0.5\) is comparable to the above determined spectral fits. For all spectral fits, the Galactic absorption was used as fixed parameter and no hint for additional absorption was found.

The X-ray spectra for the core and the jet are shown in Figure 6. No significant difference of the slope between the jet and the core spectrum was determined. The jet spectrum can be well described with a power-law model and no emission or absorption features were detected. A fit with the thermal model apec in Xspec, considering the Galactic absorption, resulted in a worse fit and a high gas temperature of \(kT = 6 \pm 3\) keV. Any
acceptable fit of a combined model using the combination of the thermal model apec (Smith et al. 2001) and a power law is dominated by the power law. Therefore, the power-law model is the favored description for the X-ray spectrum of the jet, and hence the jet is considered to be dominated by non-thermal emission.

The core and the jet spectrum both have photon indices of $\Gamma < 2$ and are thus interpreted to be IC-dominated. The core spectrum is comparable with the original definition of AP Lib being an LBL with IC dominance in the X-ray spectrum.

The luminosity of the X-ray core is $L_{\text{core,}2-10\,\text{keV}} = (1.53 \pm 0.05) \times 10^{33}\,\text{erg}\,\text{s}^{-1}$ and the jet is $L_{\text{jet,}2-10\,\text{keV}} = (5.6 \pm 0.7) \times 10^{41}\,\text{erg}\,\text{s}^{-1}$.

2.3. Variability of the X-Ray Emission

The Chandra light curve of the core region of AP Lib has been created by extracting the counts from the source region and the background region used for the spectral analysis. The energy range of 0.2–8 keV was used. The light curve has been studied in different binning, optimized for the exposure and frame time (80.08 s, 160.165 s, 320.33 s, 200 s, and 1000 s). A periodic signal was found in the extracted light curve that can be explained by the dithering of Chandra. The dither period for the ACIS detector in the X-direction is 1000 s ($Y$-direction 707 s). As mentioned, the dither period becomes visible when the source passes a node boundary, bad pixels, or the chip edges. In the case of AP Lib, the node between the detector coordinate in $X$ (CHIPX) of 511–512 is located in the dither direction. This causes lower count rates with a period of 1000 s. Except for this instrumental effect, the X-ray emission of the core is not variable. The fit of a constant to the light curve with a binning of $\sim 200$ s results in an average count rate of 0.497 $\pm$ 0.007 counts s$^{-1}$ and a fit probability of $p_{\chi^2} \sim 30\%$ ($\chi^2/\text{dof} = 61/65$) and therefore no significant variation could be detected.

On longer timescales, variation of the X-ray emission was determined with Swift observations conducted between 2007 and 2011. Ten Swift observations (ObsID: 00036341001–00036341100) were conducted in 2007, 2008, 2010, and 2011 with a total exposure of 28.2 ks. The observations on 2007 May 14 (00036341002) and 2010 February 16 (00036341009) were not taken into account due to their low exposure. For the Swift analysis, X-Ray Telescope (XRT) exposure maps were generated with the xrtpipeline to account for some bad CCD columns that were masked out on board. The masked hot columns appeared when the XRT CCD was hit by a micrometeoroid. Spectra of the Swift data in PC mode have been extracted with xselect from a circular region with a radius of 20 pixel $\approx 0.8 \text{ at the position of AP Lib, which contains 90\% of the PSF at 1.5 keV.}$ The background was extracted from a circular region with a radius of 80 pixel $\approx 3' \text{ near the source.}$ The auxiliary response files were created with xrtmkarf and the response matrices were taken from the Swift package of the calibration database caldb.

The flux in the energy range 2–10 keV has two different levels of \( F_{2-10\,\text{keV}} = (3.2 \pm 0.4) \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} \) in 2007/2008 and \( F_{2-10\,\text{keV}} = (4.9 \pm 0.5) \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} \) in 2010/2011. A fit of a constant results in a flux of \( F_{2-10\,\text{keV}} = (3.9 \pm 0.2) \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} \) and a probability of \( p_{\chi^2} = 6.6 \times 10^{-5} \). During the full time period of the Swift observations, no spectral change appeared (power law with average photon index of \( \Gamma = 1.6 \pm 0.1 \) taking into account the Galactic absorption).

To check for short-term variability, light curves with a binning of 200 s from each single observation were created and no significant variation was detected on this short timescales.

The variation is assumed to result from the core region; the jet cannot be resolved in the Swift XRT observations and the core dominates the measured flux.

In the sum of the available Swift observations in photon counting mode (total exposure of $\sim 28$ ks), the X-ray jet is not visible. Since the angular resolution of Swift is 18$''$ compared to 1$''$ of Chandra, AP Lib appears point-like and the Chandra jet is fully contained in the XRT PSF. Only possible extension at a larger scale of the X-ray jet, which could not be seen with Chandra due to the subarray used, could be determined with Swift. However, the exposure of the available Swift observation is too low to determine any very faint extension of the jet beyond 18$''$ distance to the core.

3. MULTI-WAVELENGTH OBSERVATIONS

3.1. Jet Synchrotron Emission

3.1.1. Radio Emission

Observations with the VLA on AP Lib (Cassaro et al. 1999) show the clear detection of the radio jet (see Figure 2). In VLA observations at 1.36 GHz and 4.88 GHz, the radio jet emerges along the southeast direction and bends toward the northeast after $\sim 12''$, for a total extent of $\sim 55''$ (Cassaro et al. 1999). The flux density of the jet at 1.36 GHz is given as 210 mJy and the core has a flux density of $\sim 1.6$ Jy (Cassaro et al. 1999). The observations with the D array at 1.4 GHz show a diffuse emission on an arcminute scale on the same side of the jet (Condon et al. 1998; Cassaro et al. 1999). Instead, the jet on a milliarcsecond scale emerges to the south with a position angle (P.A.) of $\sim 180^\circ$ (the VLBA monitoring program MOJAVE\(^{10}\); Lister et al. 2009). The jet on arcsecond scales determined with VLA is pointing at P.A. $\sim 120^\circ$. The further bend with an angle of $\sim 50^\circ$ results in a total change of direction of $\sim 110^\circ$ compared to the milliarcsecond scale jet.

The comparison of the kiloparsec jet in radio and X-rays reveals the same jet morphology of the emission along the SE direction (see Figure 2). An IC emission model for the X-ray jet assumes that radio synchrotron radiation is emitted by the same electrons that give rise to the X-ray radiation via Compton scattering. This is supported independently by the X-ray spectral data and the similarity of the jet morphology in the radio and X-ray bands.

3.1.2. Optical Emission

In previous works, there has been no indication for a jet in the high-energy synchrotron range. In Hubble Space Telescope observations, the elliptical host galaxy is seen, but no significant excess emission associated with the X-ray/radio jets is visible.

The core properties were studied by Westerlund et al. (1982), who used UBV measurements to separate a nucleus with a non-thermal continuum spectrum and an extended component identified as an elliptical galaxy. The optical flux of the unresolved nucleus varied between 14.6 and 17 mag in the V band during the observations mentioned in Westerlund et al. (1982) and the colors are given as \((B - V) = +0.55 \pm 0.01\) and \((U - B) = -0.57 \pm 0.01\). For the extended component, they

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\(^{9}\) http://cxc.harvard.edu/ciao4.4/why/dither.html

\(^{10}\) http://www.physics.purdue.edu/MOJAVE/
extracted an optical flux of 14.7 ± 0.05 mag in the V band after correction for reddening and determined the color of the host galaxy as \((B − V)_{\text{gal}} = 1.02\).

In 1993, Stickel et al. (1993) found that the host galaxy of AP Lib appears asymmetric and elongated toward a nearby galaxy (≈65° to the northeast). They suggested that AP Lib is an interacting system. The spectra obtained by Pesce et al. (1994) show several absorption lines for the second galaxy resulting in a redshift of \(z = 0.048\). This indicates that the host galaxy of the BL Lac object and the nearby galaxy are associated and the projected separation is 83 kpc (Pesce et al. 1994).

### 3.2. Core and Jet Spectral Distribution

The spectra obtained from the Chandra observation for the core and jet region as well as radio and optical fluxes are summarized in Figure 7. For the core distribution, the radio core flux from Cassaro et al. (1999) and the unresolved radio emission from PLANCK and Kühr et al. (1981), dominated by the core emission, are shown. The optical emission in the \(R\) and \(B\) bands are values averaged over the time range of the 2FGL catalog (Nolan et al. 2012) obtained with the ATOM telescope. It has to be considered that AP Lib is very variable in the optical band. The optical emission has been corrected for the influence of the host galaxy (Pursimo et al. 2002) and Galactic extinction (using \(E(B − V) = 0.138\); Schlegel et al. 1998). The radio emission from the jet is taken from Cassaro et al. (1999). The spectral shape of the core and jet emission is rather similar and the radio and optical emission can be described by synchrotron photons. Instead, the X-ray spectra are clearly dominated by IC emission due to their hard spectral index.

The information for the SED of the extended emission is still limited and is difficult to derive a detailed emission model. The hard spectral index of the X-ray jet suggests that the jet is dominated by IC emission in a similar way as the core.

The high-energy \(\gamma\)-ray spectrum from the 2FGL (Nolan et al. 2012) and the 1FHL (Ackermann et al. 2013) catalogs are also shown in Figure 7. It is not possible to discriminate between jet and core emission, due to the limited angular resolution of the Fermi-LAT instrument. In the 2FGL catalog, the data are obtained over two years and no strong variation was found for AP Lib. The 1FHL catalog considers one additional year of Fermi-LAT observations, and is therefore not contemporaneous with the 2FGL. The butterfly spectrum for the 1FHL data represents the 1\(\sigma\) uncertainty range of the flux density and the photon index.

### 3.3. High-energy IC Emission

The instruments that can be used to detect the high-energy IC emission above 100 MeV do not have the angular resolution to discriminate between the jet and core emission.

A GeV source, 2FGL J1517.7−2421 (Nolan et al. 2012), was detected with the Fermi Gamma-ray space telescope and can be associated with AP Lib. The flat spectrum and its flux in the Fermi energy range indicates that the maximum of the high-energy component of the emission is located at >100 MeV.

VHE \((E > 100\, \text{GeV})\) \(\gamma\)-ray emission was detected from AP Lib with the H.E.S.S. Cherenkov telescope array in 2010 June/July (Hofmann 2010).

Among all TeV BL Lac objects, AP Lib is the object with the lowest synchrotron peak frequency and the most extreme spectral indices for the radio—optical and optical–X-ray ranges (Fortin et al. 2011). Following the standard synchrotron self-Compton (SSC) model, the expected emission for AP Lib in the VHE band is well below the sensitivity of current Cherenkov telescopes and it is remarkable to detect TeV emission from this object.

### 4. SUMMARY AND CONCLUSION

AP Lib is classified as a low-frequency BL Lac object. Unexpected for this subclass, the object has been detected in the TeV band (Hofmann 2010; Fortin et al. 2011). Generally, the emission model for explaining the TeV \(\gamma\)-ray emission at the base of an SSC model requires rather high Doppler factors. The values found in spectral modeling significantly exceed the values determined from VLBI monitoring.

AP Lib shows the lowest peak frequency of the synchrotron emission and the most extreme spectral indices of all TeV BL Lac objects. This raises the question of whether or not the jet properties of AP Lib are unusual as well.

A clearly visible extended, non-thermal X-ray jet was discovered in AP Lib in the analysis of the Chandra observation of 2003 July 4. The X-ray jet is located in the southeast direction of the source and bends toward northeast comparable with the jet visible in the VLA radio observation. The radial profile of the X-ray jet reveals an extension up to \(10^\circ\), while no counter-jet could be detected. The detailed study of different profiles of the X-ray jet shows that the X-ray emission morphology is comparable with the radio emission at 1.36 GHz. Therefore it is reasonable to assume that the same electron population produces the radio and X-ray emission in the jet. The X-ray and radio jet emerges in southeast direction and turns by an angle of \(50^\circ\) between 2° and 20° and by 110° between few milliarcseconds and few arcseconds. This strong bending of the jet could be explained by a small angle of the jet axis to the line of sight of the observer. This would match the assumption of a high Doppler factor, as expected from the detection of the TeV emission for which beaming is necessary. Rector et al. (2003) concluded that LBL are seen closer to the jet axis than HBLs since they have a wide distribution of parsec- and kiloparsec-scale jet alignment angles.

BL Lac objects represent FRI galaxies in which the jet points under a small angle of \(\theta < 15^\circ\) (Marscher & Jorstad 2011) to the
line of sight. Considering this maximum angle, the deprojected length \((d_{\text{jet}})\), the deprojected range would be at \(d_{\text{jet}} \approx 54\) kpc. The possible range for the deprojected length would be up to \(d_{\text{jet}} \approx 802\) kpc, assuming a much smaller angle \(\theta \approx 1^\circ\). This maximum value for the deprojected length is comparable to the value determined by Marscher & Jorstad (2011) for OJ287 of \(d_{\text{jet}} \approx 640\) kpc for \(\theta = 3^\circ/2\).

The X-ray spectrum of the core region is described by a power law with photon index of \(\Gamma = 1.8 \pm 0.1\) and has a flux of \(\approx 10\%\) of the core flux.

Interestingly, the core and jet spectra both have a hard spectral index, indicating IC dominance. As described in, e.g., Harris & Krawczynski (2006), BL Lac objects are interpreted as beamed versions of the low-luminosity FRI radio galaxies. The IC dominance of the X-ray jet is unusual for low-luminosity AGN, as described in Harris & Krawczynski (2006) and Worrall (2009). Generally, the X-ray jet spectra for FRI are synchrotron dominated and IC spectra only appear in X-ray jets of high-luminosity sources.

All six BL Lac objects with extended X-ray jets (AP Lib (this work), S5 2007+777 (Sambruna et al. 2008), OJ287 (Marscher & Jorstad 2011), PKS 0521−365 (Birkinshaw et al. 2002), 3C371, and PKS 2201+044 (Sambruna et al. 2007)) show jet luminosities intermediate between FRI and FRII.

The spectral shape of the X-ray emission of their jets is comparable to be flat or IC-dominated. AP Lib, OJ 287, and S5 2007+777 show stronger IC dominance. Therefore, the BL Lac objects behave more similar to FRII which have mostly IC-dominated X-ray jets, although BL Lac objects are generally classified as beamed versions of FRI galaxies.

The X-ray jets of BL Lac objects are also more luminous than the X-ray jets of FRI galaxies. Compared to the sample of FRI X-ray jets of Harwood & Hardcastle (2012), the X-ray luminosity of the jets of 3C371, PKS 2201+044 (Harwood & Hardcastle 2012), and PKS 0521−365 (Birkinshaw et al. 2002) are at the high end of the luminosity distribution of FRI with \(2 \times 10^{46} \text{ WHz}^{-1} < L_\gamma < 3 \times 10^{47}\) WHz\(^{-1}\). Their X-ray spectra are rather flat and the photon indices are comparable to 2. The jet of OJ 287, S5 2007+777 (Harwood & Hardcastle 2012), and AP Lib (this work) have highest luminosities of \(6 \times 10^{47} \text{ WHz}^{-1} < L_\gamma < 8 \times 10^{48}\) WHz\(^{-1}\) and IC-dominated X-ray spectra. The X-ray jet spectra become IC-dominated with increasing luminosity.

Within the group of BL Lac objects with X-ray jets, the spectral indices of the jets also correlate with the spectral indices of the cores. The LBLs have hard core spectra and also show harder spectra in the jet. The LBLs S5 2007+777 (Sambruna et al. 2008) and OJ287 (Marscher & Jorstad 2011) have, like AP Lib, X-ray jets with IC-dominated spectra. The IBL have softer spectra in the core and their jet spectra also appear softer than the ones for LBLs. Hence, BL Lac objects with low synchrotron peak energies have higher probability of having IC dominance in the X-ray jet. AP Lib has the lowest luminosity in the X-ray jet among the jets of BL Lac objects with a clear IC-dominated X-ray spectrum. This raises the question, if the explanation for IC jets as IC scattering of CMB photons is still working or whether other external photon fields become important.

Since the core components of the X-ray emission of the BL Lac objects are also IC-dominated (only the core emission of S5 2007+777 has \(\Gamma \approx 2\)), this component is expected to reach high energies. Furthermore, the IC spectrum emerges in the X-ray regime of the core emission and the fact that the peak of the IC emission is in the GeV range (all six BL Lac objects are detected by Fermi have \(2 < \Gamma < 2.4\) in the second Fermi catalog; Nolan et al. 2012) reveal a broad IC component. This behavior of the IC scattering could also exist in the jet component.

For AP Lib it is already known that the IC component reaches TeV energies (Hofmann 2010).

The discovery of an extended X-ray jet in the TeV BL Lac object AP Lib, which is IC-dominated, therefore provides the opportunity to test the interpretation of the most common emission models as summarized in the review of X-ray jets, e.g., Harris & Krawczynski (2006).

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