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TELAMON: Effelsberg Monitoring of AGN Jets with Very-High-Energy Astroparticle Emissions

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We introduce the TELAMON program, which is using the Effelsberg 100-m telescope to monitor the radio spectra of active galactic nuclei (AGN) under scrutiny in astroparticle physics, namely TeV blazars and candidate neutrino-associated AGN. Thanks to its large dish aperture and sensitive instrumentation, the Effelsberg telescope can yield radio data superior over other programs in the low flux-density ($S\nu$) regime down to several 10 mJy. This is a particular strength in the case of TeV-emitting blazars, which are often comparatively faint radio sources of the high-synchrotron peaked type.

We perform high-cadence high-frequency observations every 2-4 weeks at multiple frequencies up to $\nu = 44$ GHz. This setup is well suited to trace dynamical processes in the compact parsec-scale jets of blazars related to high-energy flares or neutrino detections. Our sample currently covers about 40 sources and puts its focus on AGN with very-high-energy astroparticle emission, i.e., TeV blazars and neutrino-associated AGN. Here, we introduce the TELAMON program characteristics and present first results obtained since fall 2020.

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1. Introduction – Radio Spectral Monitoring of AGN in Astroparticle Physics

Blazars are active galactic nuclei (AGN) that emit violently variable broadband emission from radio to γ-ray energies. With decreasing luminosity, the peaks of their characteristic double-humped broadband spectra are shifted upwards and the high-energy emission reaches the very-high-energy (VHE) regime at TeV gamma rays. High-peaked BL Lac objects (HBLs) are canonically defined as sources whose primary (synchrotron) emission hump peaks above 10^{15} Hz [1]. In extreme blazars, the primary emission peak can reach up even higher by up to two orders of magnitude [2, 3]. Blazars are of utmost interest for astroparticle physics as possibly dominant sources of ultrahigh-energy cosmic rays and neutrinos e.g., [4, 5]. In particular, HBLs and extreme blazars have been considered in several recent theoretical works as relevant neutrino sources [6–8]. Their radio Doppler factors are surprisingly often found to differ drastically from the Doppler factors derived from high-energy observations, e.g., [9]. To explain this so-called *Doppler crisis of TeV blazars*, models have been proposed involving multiple zones on parsec scales, which can be investigated with coordinated deep multiwavelength and long-term monitoring observations [e.g., 10].

Recently, it has been shown that AGN radio monitoring programs can also play a key role in understanding very-high-energy neutrino emissions. A tentative picture is emerging in which enhanced very-high-energy neutrino emission might be characteristically associated with AGN in flaring states [11, 12]. This general behaviour has already been seen before in case of the three individual neutrino-candidate blazars PKS 1424−418 [13], TXS 0506+056 [14], and PKS 1502+106 (ATel 12996). Further radio data are urgently needed to consolidate this emerging picture.

Because of their high peak frequencies, HBL blazars are generally faint radio sources and difficult to observe, especially in single-dish monitoring programs. With its frequency agility and sensitivity, the 100-m Effelsberg telescope is able to yield superior data as compared to smaller dishes. In the TELAMON (Tev Effelsberg Long-term Agn MONitoring) program, we want to characterize the variability properties of AGN with very-high-energy astroparticle emission. *Lindfors et al.* [15] have pioneered such a study for bright VHE-emitting BL Lac objects based on OVRO 15 GHz data. They found that simple single-zone emission models cannot explain their variability patterns and conclude that continuous high-sensitivity and densely sampled radio light curves are needed to separate different jet-emission zones. Our goal is to extend such studies with TELAMON to a larger sample and to higher radio frequencies using more-sensitive radio data.

2. Observational Setup

In the first year of our program, we have observed primarily with the S14mm and S7mm receivers, which delivered simultaneous data at 19, 21, 23, 25, 36, 39, 41, and 44 GHz. We have typically used 8 subscans per cross scan for S14mm and 16 subscans for S7mm. To optimize the cadence and weather-dependent detection-rates at these high frequencies, we are now also using the S20 mm receiver (14 and 17 GHz) for the fainter targets. Our regular observations can be complemented via interleaved additional target-of-opportunity observations to increase the cadence and/or frequency coverage during periods of special interest such as planned multiwavelength campaigns or source flares. Example preliminary results are shown in Fig. 1– 5.

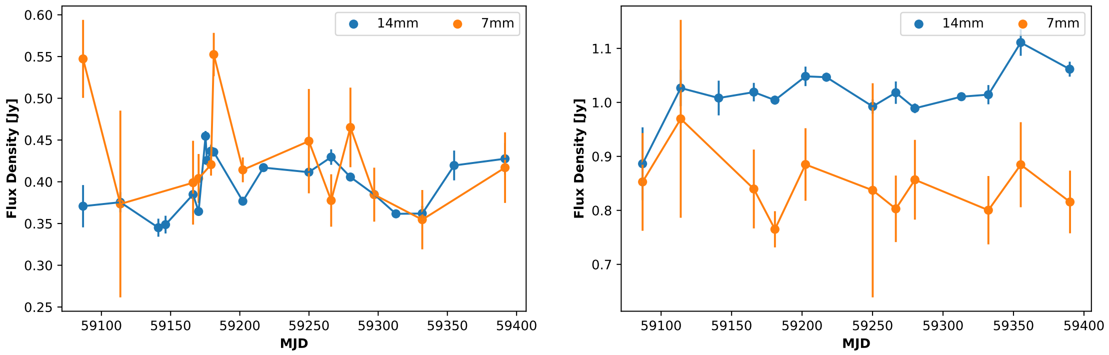

Figure 1: *TELAMON light curves (averaged over all subbands) of Mrk* 421 *(left) and Mrk* 501 *(right) between Sep* 2020 *and May* 2021.

3. The Sample

We have compiled a unique sample of TeV-detected and neutrino-candidate AGN. We exclude bright low-peaked blazars, which are well covered in other monitoring programs. As a selection criterion, we include all sources whose low-state flux density falls below 500 mJy. Sources south of +30° are also observed by ATCA in coordination with the TANAMI program [16]. This leads to a sample that is complete (down to 10–20 mJy) for HBLs and that includes a sufficient number of representatives from other source classes for comparison studies (see Table 1). Newly detected sources are dynamically included in our program if they fulfill our sample criteria.

4. High-frequency radio observations of TeV Blazars

In Fig. 1, we show example light curves of the two well-known and fairly bright HBL blazars Mrk 421 and Mrk 501 throughout the first nine months of the TELAMON program. Both sources are frequent targets of TeV telescopes like FACT, MAGIC and VERITAS and show strong radio-jet variability in between gamma-ray observations. Continuous radio monitoring is especially important to put high-energy flaring results into context [e.g., 17, these proceedings]. In Fig. 2, we show an example of a series of radio spectra for one of our program sources, S2 0109+22. This source shows flaring activity with a continuous increase in flux density over about 100 days both at 14 mm and 7 mm.

5. High-frequency radio observations of neutrino-candidate AGN

In the first year of our program, TELAMON has contributed to the rapidly evolving field of neutrino astronomy by i) high-frequency spectral radio monitoring of the blazar TXS 0506+056 that was found to show flaring activity in coincidence with the high-energy neutrino IceCube-170922A, and ii) follow-up observations of three faint compact radio sources coincident with two newly detected IceCube neutrinos.

i) TXS 0506+056 – On Sep 22, 2017, the IceCube telescope at the South Pole detected the 290 TeV neutrino IceCube-170922A in spatial and temporal coincidence with flaring activity in the

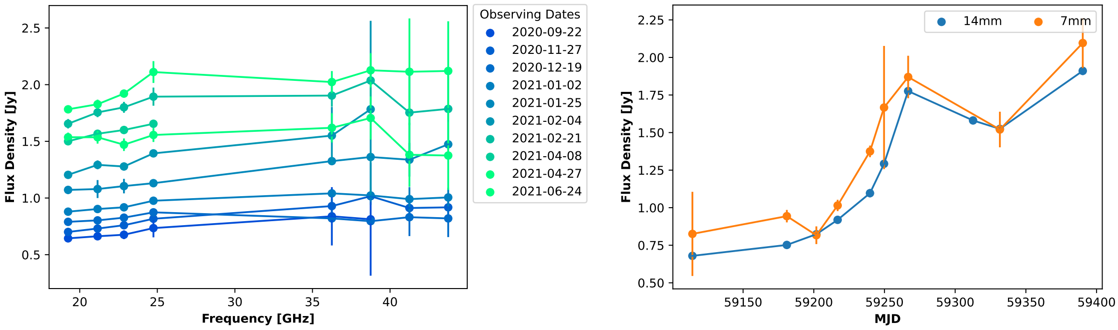

Figure 2: *Example spectra (left) and light curves (right, averaged over all subbands) for S2* 0109+22*.*

GeV gamma-ray band [18]. The chance coincidence was determined to less than 3σ making this source the most compelling blazar association of any high-energy neutrino reported so far.

The long-term multiwavelength evolution of TXS 0506+056 is shown in Satalecka et al. [19, these proceedings]. It shows that the radio emission of TXS 0506+056 had already increased strongly months before the neutrino detection and has remained in a long-term outburst stage through 2020. This behaviour is similar to the blazar PKS 1424−418 in association with the *BigBird* neutrino detected in 2012 [13]. Recent radio-monitoring results of TELAMON (and also our associated ATCA program) show that this radio outburst seems to have ended in 2021, as indicated by a steeply decreasing trend at multiple frequencies over only a few months in early 2021 [see 19, for the radio and multiwavelength light curves]. In Fig. 3, we show the radio spectral-index[1] evolution throughout this decrease. Through early 2021, the source still showed an inverted to flat spectrum. As of Mar 2021, the spectrum steepened significantly to values around −0.4 to −0.5. This is suggestive of a change into a jet state without fresh supply of high-frequency emitting plasma at the most-compact jet regions.

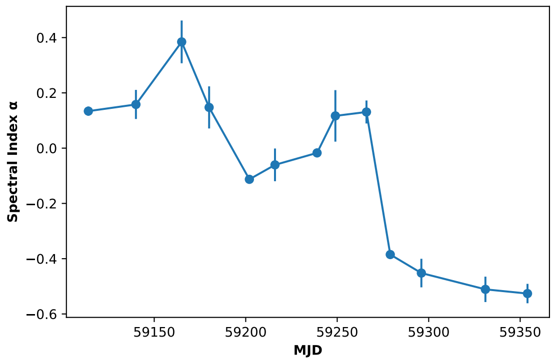

Figure 3: 14–7 *mm spectral-index evolution of TXS* 0506+056 *in early* 2021.

ii) Radio follow-up observations of new blazar–neutrino candidate associations – In mid/late 2020, the IceCube telescope reported the detection of the two bronze-alert events IceCube-201114A (GCN[2] 28887) and IceCube-201120A (GCN 28927, GCN 28943), which TELAMON followed up in the radio band:

TXS 2016+386: This is the radio-brightest AGN in the uncertainty region of IceCube-201120A. The 90 % neutrino localization is fairly large for this event. It covers about 85 square degrees and is located near the Galactic plane (GCN 28943). The positional association with TXS 2016+386 is not highly significant as 13 other catalogued 4FGL gamma-ray sources are in the same field.

[1]The spectral index α is defined via $S_\nu \propto \nu^\alpha$.
[2]https://gcn.gsfc.nasa.gov/gcn3_archive.html

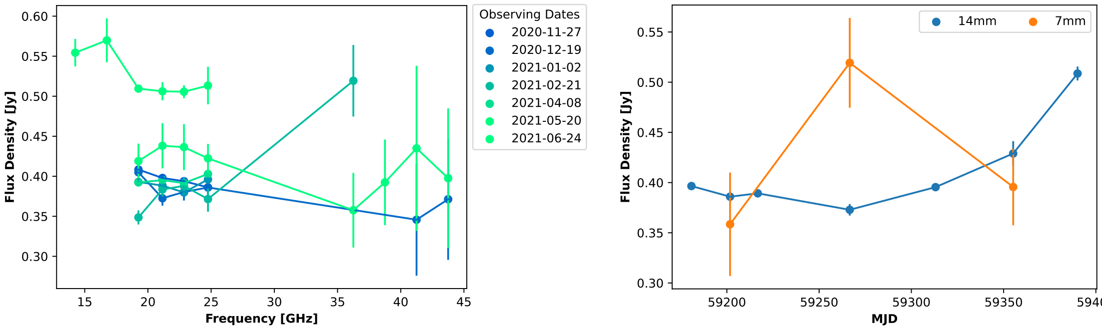

Figure 4: *Example spectra (left) and light curves (right, averaged over all subbands) for TXS* 2016+386.

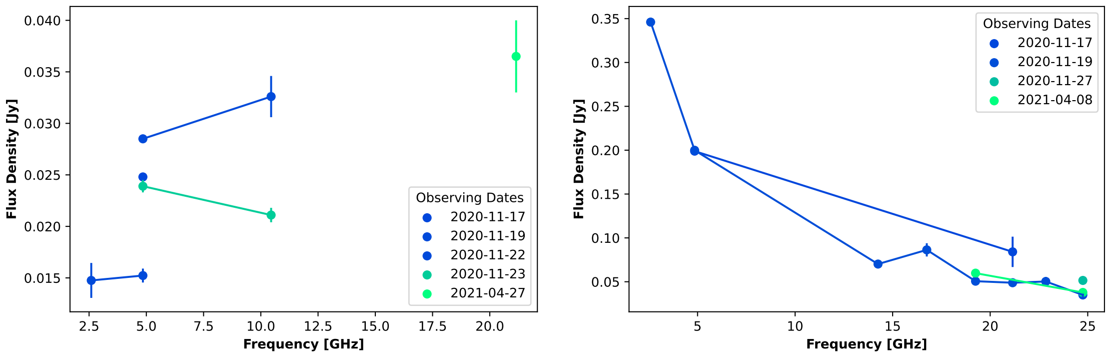

Figure 5: *Left*: *Radio spectral measurements of NVSS* J065844+063711 *performed three days after the detection of the IC* 201114*A neutrino event. Right*: *Radio spectrum of PKS* 1256+018.

We found radio flaring activity at 7 mm (see Fig. 4) followed by a pronounced increase at 14 mm. Such observations, if supported by sufficient statistics in future events, can yield valuable additional information to judge the association significance of radio flaring and neutrino emission [cf. 12].

NVSS J065844+063711: The association of this radio source with the neutrino IceCube-201114A is discussed in [20, these proceedings]. This represents only the second candidate VHE object found within the 90 % confidence region of a well-reconstructed, high-energy IceCube event. In the context of this multiwavelength effort, we could demonstrate the blazar-like flat radio spectrum of this formerly unclassified radio source (see Fig. 5 and ATel 14191).

PKS 1256+018: We found that this source, which is located in the uncertainty region of the neutrino event IceCube-201115A, is an unlikely counterpart because it shows a steep radio spectrum (see ATel 14191 and Fig. 5).

6. Outlook

We are now at the dawn of a new era in high-energy astrophysics. Current TeV gamma-ray instruments were able to detect $\sim$ 70 AGN and a few dozens of well localized high-energy neutrinos have been reported. These numbers are small compared to the over 3000 AGN known in the GeV range [21] but will increase strongly with the advent of new major facilities. The Cherenkov Telescope Array (CTA, [22]) is planned to be completed in 2025 and will observe between tens of GeV up to hundreds of TeV. In neutrino astronomy, IceCube continues to detect new events while, in the Northern Hemisphere, the new KM3NeT neutrino telescope is now coming online [23]. The construction of much larger and more sensitive neutrino telescopes is planned: e.g., the IceCube-Gen2 will be about 10 times bigger than IceCube [24]. Sensitive long-term monitoring radio programs like TELAMON with a focus on very-high-energy emitting AGN are clearly of high importance for the imminent CTA era as well as for the flourishing field of neutrino astronomy.

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Table 1: The TELAMON Sample of TeV-emitting and neutrino-candidate AGN.

ID (J2000)	Alternative Name	Class[a]	Sub-sample[b]	S^{c}_{14mm} [mJy]	Redshift	Remark[d]
0035+5950	1ES 0033+595	HBL	I	75	0.086	T
0112+2244	S2 0109+22	IBL	II	1100	–	A
0214+5144	TXS 0210+515	HBL	I	150	0.049	
0221+3556	S3 0218+35	FSRQ	I	500	0.68466	
0222+4302	3C 66A	HBL	II	1000	0.34	T
0232+2017	1ES 0229+200	HBL*	I	40	0.1396	A, G, T
0303−2408	PKS 0301−243	HBL	I	200	0.2657	A
0316+4119	IC 310	RG/HBL	I	150	0.0189	T
0416+0105	1ES 0414+09	HBL*	I	50	0.287	A, T
0507+6737	1ES 0502+675	HBL	I	50 (1)	0.341	T
0509+0541	TXS 0506+056	IBL/HBL	II	1750	0.3365	A, G, M, ν, T
0521+2121	RGB J0521+212	IBL	II	375	–	A, T
0650+2502	1ES 0647+250	HBL	I	100	–	A
0658+0637	NVSS J065844+063711	HBL	I	125	–	A, ν
0811+0237	1RXS J081201.8+023735	HBL*	I	50 (1)	0.1721	A
0913−2103	MRC 0910−208	HBL*	I	135 (1)	0.198017	A
0955+3551	3HSP J095507.9+355101	HBL*	I	10	0.557	ν
1015+4926	1ES 1011+496	HBL	I	225	0.212	ν, T
1058+2817	GB6 J1058+2817	HBL	I	100	0.4793	A, T
1104+3811	Mrk 421	HBL*	II	375	0.031	G, ν, T
1136+7009	Mrk 180	HBL	I	175	0.045278	
1145+1936	3C 264	RG	I	325	0.021718	A, T
1217+3007	ON 325	HBL	II	450	0.131	A
1221+2813	W Comae	IBL	II	475	0.102	A, T
1221+3010	1ES 1218+304	HBL*	I	68	0.184	A, T
1230+2518	ON 246	IBL	II	400	0.135	A
1422+3223	OQ 334	FSRQ	II	775	0.681	
1427+2348	OQ 240	HBL	II	400	0.647	A, M, ν, T
1428+4240	1ES 1426+428	HBL*	I	30	0.129	G, T
1443+2501	PKS 1441+25	FSRQ	I	150	0.94	A
1518−2731	TXS 1515−273	HBL	I	225	0.1281	A
1542+6129	GB6 J1542+6129	IBL	II	115	0.507	M, ν
1555+1111	PG 1553+113	HBL	I	300	0.49	A, ν, T
1653+3945	Mrk 501	HBL*	II	1000	0.034	G, T
1728+5013	I Zw 187	HBL*	I	125	0.055	G, T
1743+1935	1ES 1741+196	HBL*	I	175	0.084	A, G
1813+3144	B2 1811+31	FSRQ	I	100	0.117	ν
1943+2118	HESS J1943+213	HBL*	I	~ 20 (2)	–	A
1958−3011	1RXS J195815.6−301119	HBL*	I	100 (1)	0.119329	A
1959+6508	1ES 1959+650	HBL*	I	225	0.048	G, T
2018+3851	TXS 2016+386	HBL	I	400	–	
2158−3013	PKS 2155−304	HBL	I	325	0.116	A, T
2243+2021	RGB J2243+203	HBL*	I	115 (1)	0.119329	A
2347+5142	1ES 2344+514	HBL*	I	150	0.044	G, T

[a] FSRQ: flat-spectrum radio quasar – LBL: low-peaked BL Lac – IBL: intermediate-peaked BL Lac – HBL: high-peaked BL Lac (extreme blazars are marked as HBL*) – RG: Radio galaxy; [b] I) Observations in the 20 mm and 14 mm bands, II) Observations in the 14 mm and 7 mm bands; [c] Median flux densities from our first 9 months of observations at 14 mm wavelength, or estimated from 1) NED, 2) Gregory & Condon, 1991; [d] A: ATCA monitoring; T: Frequent TeV observations or monitoring by FACT, H.E.S.S., MAGIC or VERITAS; G: GMVA observations in 2020; M: in coordination with MOJAVE; ν: Positionally associated with a high-energy IceCube neutrino.