

Review

Multifrequency Studies of Active Galactic Nuclei in the *Planck* Satellite Era

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Abstract: The multi-epoch single-survey *Planck* satellite data have given a rare glimpse into how the radio spectra of active galactic nuclei (AGN) evolve in time. Using *Planck* and simultaneous auxiliary radio data ranging from 1 GHz to 857 GHz, spectra for 104 bright northern extragalactic radio sources (most of them AGN) have been assembled; in these, the various stages of flare development can be identified. The results are compared with theoretical models describing relativistic jets. Evidence for particularly flat high-frequency radio spectra is found, indicating a harder accelerated electron energy spectrum than usually assumed. A set of sources also shows signs of intrinsic cold dust.

Keywords: active galactic nuclei; radio spectra; relativistic jets

1. Introduction

The synchrotron spectra of active galactic nuclei (AGN) are usually flat, due to several emission components (i.e., shocks) moving in the relativistic jet on top of a constant, quiescent jet [1,2]. Typically the radio spectrum of such a shock component peaks at higher frequencies and then moves towards lower frequencies, creating the flat overall impression when combined with the spectra of several other components. It requires extensive and time-consuming multifrequency campaigns to actually follow such a spectral evolution; the timescales are in the range of a few weeks to even years. It is difficult to arrange exhaustive observing time for such efforts, not to mention that instruments operating at high radio frequencies are rather rare or non-existent.

The *Planck* satellite was an ideal tool for spectral studies of bright AGN. It was operated between May 2009 and October 2013 (including the extended missions), and during this time it surveyed the whole sky several times [3]. The main mission of the satellite was to measure the cosmic microwave background (CMB), but because of the observational strategy of making all-sky maps, it observed all sources in front of the CMB as well, including AGN. One scan of the whole sky took around six months, after which the satellite started another scan. Due to the scanning strategy, this meant that one data point for a source was produced at least once in six months. The number of data points per source also depended on the location of the source in the sky; for some sources (particularly near the ecliptic poles), there are more data points.

The satellite had a broad frequency range: it operated receivers at 30, 44, 70, 100, 143, 217, 353, 545, and 857 GHz. Another great advantage was that the multifrequency data produced by *Planck* were simultaneous. The variability of AGN can be rapid, from a couple of weeks to months, and data must be taken within a fairly short period of time if they are to be used for snapshots describing the spectral states of the sources.

Radio spectra using *Planck* and a set of ground-based instruments were collected for a sample of 104 bright, northern-to-equatorial extragalactic sources, mainly AGN. The first part of this work was published in Planck Collaboration XV 2011 [4], where data from the *Planck* Early Release Compact

Source Catalog (ERCSC) were used to create radio spectra and spectral energy distributions. One of the main findings in this paper was that the high-frequency spectral indices are surprisingly flat, indicating a harder original accelerated electron energy spectrum than usually assumed (around 1.5 instead of the canonical 2.5). This has implications on the acceleration mechanism at work in these sources. However, the *Planck* data used in that study were mostly only near-simultaneous, as most of the ERCSC data were averages of two all-sky scans.

The full *Planck* mission data (four individual all-sky surveys) for the same sample were published in Planck Collaboration Int. XLV 2016 [5]. Here the data are genuinely simultaneous for all four surveys. In this paper, these latest multi-epoch, single-survey *Planck* results are reviewed. In addition to *Planck* data, data from auxiliary ground-based instruments are used. Data taken within two weeks of the *Planck* pointings are considered to be simultaneous.

2. Source Sample and Observations

The 104 northern and equatorial extragalactic radio sources in the sample (mostly AGN) all have declination equal to or larger than -10° and average 37 GHz flux larger than 1 Jy. The sample was further divided into subsamples: high-polarization quasars (HPQ; 40 sources), low-polarization quasars (LPQ; 14 sources), BL Lac objects (BLO; 24 sources), quasi-stellar objects (QSO; 17 sources), radio galaxies (GAL; eight sources), and one unidentified source. High and low polarization modes are defined based on optical polarization larger or smaller than 3% in the literature, respectively. However, for many quasars, this information does not exist. The sample is listed in full in Planck Collaboration Int. XLV 2016 [5].

The single-survey data from the *Planck* satellite were derived using dedicated Mexican Hat Wavelet 2 source detection and flux density estimation pipelines in the Planck Data Processing Centres. The Second Planck Catalogue of Compact Sources [6] contains information about the details of the data extraction and the catalogue of sources. However, it should be noted that the flux densities presented in the catalogue are averages, and not single-survey fluxes.

An extensive multifrequency observing campaign using ground-based instruments was arranged during the *Planck* mission. This provided auxiliary observations at several additional radio frequencies, listed in Table 1. For the full description of the observations, see Planck Collaboration Int. XLV 2016 [5]. The range of observations collected for the sample therefore extends from around 1 GHz to 857 GHz.

Table 1. Ground-based instruments that provided auxiliary multifrequency data.

Observatory	Observing Frequencies (GHz)
Metsähovi Radio Observatory	37
Owens Valley Radio Observatory	15
U. Michigan Radio Astronomy Observatory	4.8, 8.0, 14.5
RATAN-600	1.1, 2.3, 4.8, 7.7, 11.2, 21.7

3. Results

3.1. Spectral Shapes

Putting all the simultaneous data together resulted in four radio spectra per source, separated by six months. Over the total period of around two years, various kinds of spectral shapes could be seen; the main types being evolving shocks, achromatic variations, and non-variable spectra.

The variability caused by evolving shocks is best described by the Marscher & Gear model [1]. Here, shock-like disturbances grow and decay in the relativistic jet, causing the characteristic motion of the shock turnover peak from high to low frequencies, and the time delays between frequencies. This behaviour has been successfully modelled in several cases in the past (for example, [7–10]). The flares seen in frequent flux density monitoring (such as the Metsähovi Radio Observatory’s quasar

monitoring programme) are taken to imply that their origin is in the shocks growing and decaying in the jet.

However, during the *Planck* lifetime, there were only a few large, well-defined, and complete flares in a handful of sources. Furthermore, if the observations are not timed ideally, the beginning or the end of the flare can be easily missed. In most cases, the complete evolution of the flare could not be followed due to the relatively sparse sampling of *Planck* (i.e., six months), and therefore clear signatures of evolving shocks could not be seen. However, sources 0420+014 (OA 129), 0851+202 (OJ 287), 1156+295 (4C 29.45), 1226+023 (3C 273), and 2251+158 (3C 454.3) exhibited large isolated flares with good multifrequency sampling. OJ 287 and 3C 454.3 had their strongest ever flare measured at 37 GHz during the mission, and even if the evolution of shock components can be seen in each of the five sources, in these two it is very clear.

For most sources, the variability is simply achromatic, where the spectra are moving up or down, or they are not variable at all. In contrast, Angelakis et al. (2012) [11] found that in a study using 4.5 years of data, including mm wavelengths, only eight out of 78 sources exhibited achromatic variability.

For at least seven sources, a clear upturn at the highest radio frequencies was found, indicating contribution from dust. The key question is whether the origin of the dust is intrinsic or contamination by Galactic cirrus. This is discussed in more detail in Section 4.2.

3.2. Spectral Indices

The spectra were fitted with a broken power-law model [12] to determine the spectral indices and break frequencies between the low and high frequencies (LF and HF, respectively). As we only considered sources for which there were observations in at least five frequencies, we ended up with 62, 60, 58, and 51 sets of spectral data in each of the *Planck* surveys. The average spectral indices and break frequencies per source class and *Planck* survey are shown in Table 2. The suspected dusty sources were excluded, and as a consequence, GAL sources were left out, as their number was reduced to only four.

Table 2. Spectral indices and break frequencies.

Class	Survey 1			Survey 2			Survey 3			Survey 4		
	α_{LF}	α_{HF}	ν_{br}									
BLO	0.005	−0.454	81.5	0.096	−0.369	61.3	0.082	−0.409	57.2	−0.090	−0.371	37.2
HPQ	0.008	−0.560	61.2	0.030	−0.647	65.2	0.000	−0.481	61.2	0.027	−0.535	55.0
LPQ	0.081	−0.784	54.1	0.120	−0.695	48.8	0.074	−0.640	42.0	−0.080	−0.679	43.2
QSO	0.205	−0.495	55.5	0.017	−0.530	72.6	0.230	−0.410	44.7	0.150	−0.541	43.5

The average spectral indices confirm what was found in the *Planck* ERCSC paper [4]: the LF spectral indices are close to zero, as expected, and the HF indices are exceptionally flat. 42% of the HF indices are flatter than −0.5, as opposed to the expected −0.7 of the canonical optically-thin synchrotron spectrum. The range of the observed HF spectral indices is around −0.2 to −0.7, which leads to an electron energy spectrum index of around 1.5.

There are also differences between the AGN classes. The LF indices look fairly similar; however, the HF indices, particularly of LPQs and BLOs for all four surveys, come from different distributions ($P_{\text{Kruskal-Wallis}} = 0.001\text{--}0.008$, depending on the survey). The LPQ radio spectra are steeper than those of BLOs. The same trend can be seen between HPQs and BLOs in survey 2 ($P_{\text{Kruskal-Wallis}} = 0.001$). This may hint at differences in the electron energies of the two classes.

The break frequencies are rather higher than expected, usually tens of gigahertz. The sources are not, however, defined as Gigahertz peaked-spectrum sources, as they show strong variability. The break frequencies also change from survey to survey, and vary between sources. There are no significant differences between the break frequencies of the various AGN classes.

4. Discussion

4.1. Variability of the Radio Spectra

So far, comparisons between theoretical models that aim to explain the variability in AGN have been performed at fairly low frequencies, mainly because higher frequency data have not been available in large enough quantities. They have also usually concerned only the strongest flares. Indeed, in the simultaneous *Planck* and multifrequency data from four epochs, evolving shocks—like those in the Marscher & Gear model—only appear in the radio spectra of large, well-defined flares. This is true for the five showcase sources in the *Planck* study. If we see such a flare in the Metsähovi monitoring data, and the *Planck* observations cover the entire period, a component is seen in the radio spectra with the peak moving (as expected) from high to low frequencies. In contrast, achromatic variability behaviour—with spectra rising and decreasing concurrently at almost all frequencies (excluding the very lowest ones)—is dominant in most other sources.

The turbulent extreme multi-zone model (TEMZ; [13,14]) may explain both of the above variability types in AGN. In this model, a disturbance passes through the radio core (i.e., a standing conical shock) and random cells are shocked, producing emission—the flux density of which is the sum of emission from each cell. This process can also generate achromatic variations, and can therefore also explain the variability behaviour of the *Planck* AGN sample.

Variability may also be caused by changes in the jet direction. This would create achromatic variations by changing the Doppler factor. However, it is easy to rule out this kind of geometric variability, because its typical signatures, periodicities, or repeated variability patterns have not been observed over long periods of time.

4.2. Dusty Sources

Several sources show an upturn in their HF spectra, and contamination from Galactic cirrus clouds around temperatures 15 K to 25 K is the most likely explanation. This complies with the expected spectral index (ν^3 to ν^4) of such clouds. Nevertheless, it is possible that the dust is intrinsic in some AGN, remaining from the starburst phase. Most likely the infrared-emitting dust components would be overrun by the non-thermal emission of the AGN, even in the brightest infrared galaxies; however, the possibility of vast amounts of intrinsic dust, detectable at the highest *Planck* frequencies, is intriguing.

We picked seven sources exhibiting clearly rising HF spectra for further examination. They are shown in Table 3, ordered by their redshift. Almost all of the high-redshift sources are located in heavily confused areas in IRAS and *Herschel* maps, and they have also been marked with cirrus flags in the *Planck* Catalogue of Compact Sources [15]. The only exception may be 2037+511.

Table 3. Possibly dusty sources with rising HF spectra, ordered by their redshift.

Source Name	z
0238-084	0.005
0430+052	0.033
0415+379	0.049
0446+112	1.207
1954+513	1.223
0333+321	1.258
2037+511	1.686

The low-redshift sources, however, are located in clear areas. For these, the possibility of cold intrinsic dust at the temperature of 20 K is a genuine possibility. These sources have been observed earlier at mid-infrared, and if those observations are added to the spectra, the emerging infrared component can be explained by a single dust component with the temperature of 15 K and the peak

of the spectrum $\log v_{\text{peak}}$ located at 12.2 (around 200 μm). Further studies at infrared frequencies are definitely required. For example, dust in AGN has been observed by the *Spitzer Space Telescope* [16], which detected two sources in the *Planck* sample—namely, 1222+216 and 2230+114 (CTA 102). There is a small upturn in the *Planck* data of the latter; however, the frequency ranges of the two satellites are considerably different.

5. Conclusions

The main conclusions from the *Planck* and multifrequency study of 104 bright AGN are as follows.

- (1) The high-frequency spectra are flat, ranging between -0.2 and -0.7 , indicating an original electron acceleration spectrum index as hard as 1.5.
- (2) The break frequencies are strikingly high (tens of gigahertz), and are variable from source to source and between epochs.
- (3) The TEMZ model could explain the variability of the radio spectra by characterizing both evolving shocks and achromatic variability, both seen in the sources in the *Planck* sample.
- (4) Intrinsic cold dust may be present in some (low-redshift) AGN that show an upturn in their high-frequency *Planck* spectra. In high-redshift sources, this is probably due to contamination by Galactic cirrus.

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Conflicts of Interest: The authors declare no conflict of interest.

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