From Radio with Love: an overview of the role of radio observations in understanding high-energy emission from active galaxies

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Abstract. The gamma-ray satellite *Fermi* and the ground based TeV facilities MAGIC, VERITAS and HESS have ushered in a new era in the observation of high-energy emission from active galaxies. The energy budgets of these objects have a major contribution from gamma-rays and it is simply not possible to understand their physics without high-energy observations. Though the exact mechanisms for high-energy production in galaxies remains an open question, gamma-rays typically result from interactions between high-energy particles. Via different interactions these *same* particles can produce radio emission. Thus the non-thermal nature of gamma-ray emission practically guarantees that high-energy emitters are also radio loud. Aside from their obvious role as a component of multiwavelength analysis, radio observations provide two crucial elements essential to understanding the source structure and physical processes of high-energy emitters: very high timing resolution and very high spatial resolution. A brief overview of the unique role played by radio observations in unraveling the mysteries of the high energy Universe is presented here.

1. Introduction

A curious dichotomy is associated with the state of our understanding of the physics of active galaxies. In the decades since their discovery, increasingly detailed (in many senses) observational data, ever more sophisticated modeling and profound theoretical ideas have combined to produce a remarkably coherent basic picture of what might go on in these objects. There is the exceptionally luminous core powered by accretion onto a supermassive blackhole. The trapped gas settles into an accretion disk which heats up due to dissipative processes that move matter inwards and angular momentum outwards. Hovering above the accretion disk is a hot corona which can inverse-Compton scatter photons to X-ray energies. There is the cold atomic material that is excited by radiation from the accretion disk and produces a range of emission lines particularly at optical/UV frequencies and the absorption features seen in the UV and X-ray. And in a small but important fraction of cases, highly collimated 'jets' emerge and travel at relativistic speeds possibly providing a link between the central black hole and the galactic environment (e.g.[1], [2], [3]). It is almost possible to believe we essentially understand AGN with only small details to be cleared up.

However, one simply has to take a step back to realize that just about every piece of this neat picture is rather less than clear: details of the central engine (such as the role of spin), accretion

and disk formation are unknown. The production, acceleration and collimation of jets and how they remain collimated are open questions, indeed even their composition (positron-electron or proton-electron) is not known. The origin of the high energy emission remains a mystery. Half a century after their discovery, the fundamental questions about AGN remain unanswered.

2. Fermi meets Jansky

Since the seminal detection of γ-rays from AGN (particularly blazars) by the EGRET instrument on the Compton Gamma Ray Observatory (e.g. [4]), it has become clear that high energy radiation forms a major part of the energy budget of AGN and observations at these energies are essential to understanding them. The Large Area Telescope instrument aboard the *Fermi* Gamma Ray Space Observatory (hereafter *Fermi/LAT*; [5]) and three major ground based TeV facilities MAGIC, HESS and VERITAS, have dramatically opened up this part of the electromagnetic spectrum to observation with sensitivity, field of view, range of cadence, and resolution that is orders of magnitude better than before.

Another crucial observational breakthrough relates to a basic characteristic of AGN: they radiate throughout the electromagnetic spectrum (and possibly emit non-electromagnetic messengers, see below) and the radiation at all wavebands varies in ways that appear to be linked in very complex ways to variations at other wavebands. Thus *simultaneous* and *multiwavelength* observations are the only way AGN behavior can be constrained. The availability of the above high energy instruments, the presence of X-ray and UV instruments on satellites (e.g. *Swift*; [6]), backed up by optical, submillimeter and radio facilities on the ground have made it feasible to monitor AGN simultaneously across the spectrum for the first time since their discovery!

The role of radio observations in understanding the high energy emission from AGN is much greater than the obvious need for radio data to construct the spectral energy density (SED) of AGN. Gamma rays typically result from interactions between high energy particles (see below for a brief discussion) and, with different interactions, these *same* particles produce radio emission. Thus, the non-thermal nature of γ-ray emission almost guarantees that they will be radio emitters. This is incredibly useful because radio observations provide two handles that let us get a grip on the source structure and physical processes of AGN. The first is timing resolution. Radio telescopes are able to monitor both rapid flares and slow changes in flux. Thus, they are used to search for periodicities from minutes to years constraining physical processes responsible for high energy radiation from AGN. The second useful and indeed unique handle provided by radio observations is very high spatial resolution. The technique of radio interferometry, particularly Very Long Baseline Interferometry (VLBI), provides the highest angular resolution possible of any observational technique, often better than a milliarcsecond. This means that VLBI monitoring of AGN jets provides the *only direct measure* of relativistic motion in AGN jets, probing intrinsic jet parameters such as speed, Doppler factor, opening and inclination angles, all of which are essential constraints on jet physics and tests of the relativistic-beam model (e.g. [7]). Further, the unmatched resolution of VLBI makes identification of the location and extent of emission regions possible at a level of detail not available with any other observational technique (e.g. [8]).

Given that resolution depends directly on frequency, it is ironic that the magic of interferometry, as well as the likely origin of high energy and radio emission from the same population of particles, have made radio observations uniquely useful in studying the origins of emission from the other end of the electromagnetic spectrum. Counterintuitive as it might seem, radio and high energy studies of AGN are closely linked and essential to maximizing the scientific output from each other.

3. Origin and nature of high energy emission from AGN

AGN remain, by far, the largest class of identified *Fermi/LAT* detections [9] confirming the finding originally made by EGRET that the SEDs of blazars are often dominated by gamma-ray emission. While this link is clear, the underlying mechanism(s) is less so with a variety of models attempting to explain the origin of high frequency emission (see [10] for a review). Briefly, the spectral energy (νF_ν) distributions (SED) of blazars have two maxima. It is fairly well established that synchrotron emission from relativistic electrons in the jet produce the low energy peak in the radio-to-infrared band [11], [12]. The origin of the high energy hump remains a major open question. It could arise from inverse-Compton scattering of the same electron population off synchrotron photons, the so-called Synchrotron Self Compton model [13], [14]. Or it could arise from inverse-Compton scattering of photons external to the jet by the relativistic electrons within the jet. Depending on the possible sources of the external photons (e.g. cosmic microwave background radiation, BLR, etc) there are several flavors of this External Compton model [15]. An entirely different class of models suggest this high energy component of the SED arises from hadronic processes involving high energy protons which produce neutral and charged pions that decay into electrons and positrons which in turn produce γ-ray photons and neutrinos e.g. [16] [17]. Dynamic, quasi-simultaneous observations across the electromagnetic spectrum are needed to construct SEDs that can be used to distinguish between these models and understand emission from AGN. If the hadronic models are correct, there is the intriguing possibility of going beyond traditional photon based astronomy to studying AGN physics using neutrinos as messengers thanks to neutrino detectors such as ANTARES, KM3Net and IceCube.

4. High cadence, broadband, multifrequency monitoring of total and polarized flux density and spectral evolution

Rapid variability of the total and polarized flux density in all wavebands is a defining property of AGN and one that has great potential to constrain physical parameters and discriminate between different models attempting to understand AGN. Explanations for variability include (but are not limited to) accretion disk instabilities [18], the shock-in-jet models [19], [20], the collision of relativistic plasma shells traveling at different speeds [21], lighthouse effects arising from rapidly rotating plasma in the vicinity of a rotating black hole [22] and magneto-centrifugal acceleration of beams of particles [23]. Monitoring the variability of their SEDs at all wavebands can discriminate between these different scenarios/models. It can also yield information about linear scales that cannot be reached even by interferometry. For a few recent high impact results see [24], [25], [26], [27], [28],

As has been clear from early in the mission lifetime of EGRET, monitoring at radio wavelengths is particularly important for understanding gamma-ray emission from and the physics of AGN. The relative timing of gamma-ray and radio flares can constrain both the mechanisms responsible for them as well as the location where they originate e.g. [29]. Flux density monitoring to measure the evolution of the radio emission with time indirectly reveals when relativistic electrons are being injected into the jet. AGN are highly compact and have a large optical depth to synchrotron self-absorption. Hence, radio observations are best made at the higher radio frequencies in the optically thin part of the radio spectrum if we are to probe close to the center of these sources where the gamma-ray emission is likely generated [30]. Early work with EGRET data [31] suggested that high radio frequency flares precede gamma-ray flares but the sparseness of the EGRET data made this result tentative. If true, this would imply that the gamma-ray emission results from shock enhanced electron energies and magnetic field strengths and support the idea that the IC seed photons originate from within the jet rather than externally. Further, this putative timelag between the radio and gamma-ray flares (and the relativistic speeds of the jets) implies that the gamma-ray emission originates parsecs downstream of the base of the radio jet. This leads to the exciting possibility that these

shocked regions, these birthplaces of gamma-ray emission, could be directly imaged using high radio frequency VLBI. In combination with kinematic parameters gleaned from multi-epoch VLBI (see below), such constraints on the size and flux density of shocked regions would allow quantitative modeling of inverse Compton models for gamma-ray emission.

However, before the launch of *Fermi*, a preponderance of theorists seemed inclined towards an external source for the seed photons that produce gamma-ray emission by IC scattering off relativistic jet electrons, implying production within about a tenth of a parsec of the central black hole. Two good reasons for this view are the short time-scales of flux variability which are easier to explain close to the black hole and the availability of potential external sources of seed photons such as the BLR or the dust torus [32]. The post-Fermi radio data continues to challenge this notion though not in a completely consistent way. For example, [8] have used VLBI and single-dish radio observations with optical and gamma-ray data on OJ287 to show that the gamma-ray flare originates > 14 parsecs from the radio core. In general gamma-ray emission appears to correlate well with ejection and apparent speed of VLBI components [33] and with the passage of these components through the millimeter core [34]. Meanwhile optical polarization observations suggest that gamma-rays could be produced all along the inner jet, from the core to some 20 parsecs downstream [35].

Another important use of such monitoring data is the study of the radio-gamma connection in AGN. For example, [36] have used both archival and concurrent radio data to study the statistical significance of the correlation between gamma-ray emission and radio emission from AGN. They find a positive correlation of high significance for all types of AGN (and for FSRQs and BL Lacs separately) with the significance greater for concurrent data. They also find a possible dependence of the correlation on the gamma-ray energy band.

This importance of high cadence, broadband multifrequency monitoring in general and radio monitoring in particular has been appreciated for some time and dedicated radio monitoring programs such as the centimeter band flux and polarization monitoring program at the University of Michigan [37], the 22/37 GHz monitoring program of the Metsähovi Radio Observatory [38] and the simultaneous 1-22 GHz monitoring with RATAN-600 [39] have been making important contributions for decades. The scientific dividend from such studies got a boost from the launch of *Fermi* and the availability of the ground based TeV experiments leading to the launch of dedicated new programs such as FGAMMA, the OVRO program and TANAMI.

The F-GAMMA (Fermi-GST AGN Multifrequency Monitoring Alliance) program monitors the flux density and polarization of a sample of ~ 60 *Fermi/LAT* sources at monthly intervals [40]. It observes with radio, millimeter, submillimeter, infrared and optical instruments including the 100 m Effelsberg telescope in Germany and the 30 m IRAM telescope at Pico Veleta, Spain. A much larger sample of over 1500 blazars is monitored about twice a week by the 40 m Owens Valley Radio Telescope (OVRO; [41]).

All of the above monitoring programs use instruments located in the northern hemisphere and thus their coverage does not extend very far into the southern hemisphere. The Tracking AgN with Austral Milliarcsecond Interferometry (TANAMI; [42], [43]) program fills this gap with two separate and complementary monitoring programs that concentrate on the sky south of -30 degrees declination. The first has used a 30 m dish at Ceduna in South Australia to regularly monitor sources at 6.7 GHz since August 2007 generating well-sampled lightcurves. The other program has used the Australia Telescope Compact Array (ATCA) since October 2007 to monitor at a lower cadence (~ 8 epochs a year) but in 4 frequency bands in the 4.8 to 40 GHz range to follow the evolution of the radio spectrum.

5. High resolution (VLBI), multi-frequency monitoring of parsec scale jet structure

Clearly observations at all wavebands are needed to understand AGN. However, multi-epoch VLBI observations provide the only direct measure of relativistic motion in AGN jets. So they are the only means of measuring intrinsic jet parameters such as speed, Doppler factor, opening angle, inclination angle, magnetic field strength and magnetic gradients that are necessary inputs to models of jet behavior. They are also the only way to associate morphological changes (such as component ejections or changes in magnetic field strength/orientation) close to the central black hole to activity in other wavebands, which is a powerful diagnostic of emission processes. Further, they have the potential to locate and constrain the size of emission regions in conjunction with high energy and intermediate energy observations. Key questions that can only be addressed with the help of VLBI monitoring include:

- Where are the gamma-rays produced in blazar jets? How big are these emission regions?
- How do gamma-ray variability patterns relate to intrinsic jet parameters?
- Are radio and gamma-ray emission beamed with the same Lorentz factor?
- What are jets made of? Are they purely leptonic or do they have a hadronic component?
- Are gamma-ray flares accompanied by jet-component ejections?
- Why are some blazars bright in gamma-rays while others are not?
- Under what conditions can non-blazar AGN become bright gamma-ray emitters?

When VLBI arrays are capable of measuring polarization, Very Long Baseline Polarimetry (VLBP) yields the magnitude and orientation of jet magnetic fields which enable studies of the collimation and acceleration of jets, jet composition and kinetic luminosity. VLBP can also trace magnetic fields external to jets e.g. in sheaths and boundary layers. Further, as a tracer of jet hydrodynamics VLBP is extremely useful for the identification of shocks, shears and aberration. VLBP observations have already shown that linear polarization is low (just a few percent) in the core region but is typically higher (in the tens of percent) in jets. There are extended regions in jets where the magnetic field is orthogonal to the jet direction and remains so even when the jet bends significantly. There are now several examples of jets showing a 'spine-sheath' structure. Faraday rotation gradients across jets appear to be common and there is some evidence for the existence of helical magnetic field structures that have been proposed by some theorists [44], [45].

Major VLBI monitoring programs include MOJAVE, the Boston University blazar group, VIPS and TANAMI. Though there is some overlap, these programs are largely complementary and together they effectively wield the power of VLBI monitoring. We will take a quick look at each program and then summarize the key findings so far.

With its origins in the VLBA 2cm Survey (1994-2002; [46]), the MOJAVE (Monitoring Of Jets in Active galactic nuclei with VLBA Experiments; [47]) program is probably the most comprehensive VLBI monitoring program and it includes many of the longest time baseline, well sampled VLBI observations available. MOJAVE makes full polarization observations of about 300 sources using the ten telescopes of the VLBA (Very Long Baseline Array; [48]) at a frequency of 15 GHz. MOJAVE observes a flux limited gamma-ray selected sample based on the *Fermi* 11 month list with a matching radio sample with $S_{5\,GHz} > 1.5$ Jy during the 11 month period. Its goal it to study the structure and kinematics of AGN jets and their connection to data at other wavebands including high energy emission. MOJAVE's large sample is particularly suitable for statistical studies.

The Boston University blazar group uses millimeter wavelength VLBI imaging to follow jet evolution particularly the motions of superluminal 'knots' in the jet. They also use the VLBA about once a month, to make full polarization observations of 34 blazars at 43 GHz [49]. They

associate optical, X-ray and gamma-ray flares with a superluminal knot if a flare is coincident with the passage of the knot through the 43 GHz core which is several parsecs downstream of the central black hole. This group also has an optical polarization monitoring program and during a flare it attempts to match the optical polarization angle to a VLBI feature with a similar value of polarization angle. They are attempting to use the timelag between high energy variations and changes in optical and millimeter band fluxes to determine the location of X-ray and gamma-ray emission sites.

The VIPS (VLBA Imaging and Polarimetry Survey; [50]) is a high dynamic range, full polarization survey of a large sample of about 1100 sources at 5 and 15 GHz using the VLBA. The sources have a flux limit $S > 85$ mJy at 8 GHz, are located at declination > 20 and $|b| > 10$ in the SDSS (Sloan Digital Sky Survey) northern cap to make identification and redshift information easier to obtain. With a flux limit almost an order of magnitude below that of MOJAVE and other surveys, it is able to study the large population of relatively faint radio sources finding, for example, that at lower flux levels the radio and gamma-ray flux densities are not directly correlated. Aside from characterizing *Fermi* sources, VIPS aims to understand polarization properties of different AGN classes, study AGN environments and to find close binary black hole systems.

The TANAMI program [43] makes dual frequency (8 and 22 GHz) observations about every two months, measuring spectral indices of jet features and their time evolution. It is the only program observing sources in the southern third of the sky which not only significantly improves the statistics for jet kinematics and flare-ejection studies but allows access to some of the most interesting individual sources in the sky e.g. the nearby radio galaxy Centaurus A. TANAMI uses the five telescopes of the Australian Long Baseline Array (LBA; e.g. [51]) augmented by two German telescopes (at Concepcion, Chile and O'Higgins, Antarctica), a telescope in Hartebeesthoek, South Africa and a telescope at NASA's Deep Space Network in Tidbinbilla, Australia. The array has recently been expanded with the addition of three new telescopes in Warkworth, New Zealand, in Yarragadee, Western Australia and in Katherine, in the Northern Territory. The TANAMI sample currently includes about 80 sources and is being expanded to include new *Fermi/LAT* detections. TANAMI recently published the highest resolution images ever made of Centaurus A [52] as well as the dual-frequency spectral index distribution along its jet (see Fig. 1). The jet of Centaurus A appears to be already well collimated on scales of 10^{15} m and multiple possible sites for the production of high energy radiation can be identified.

As the large number of published results testify, VLBI monitoring is rapidly improving our understanding of AGN but many of the deepest questions require a longer timeline of observations. However, it is already clear that apparent superluminal motion is quite common with the Lorentz factor distribution going up to $\Gamma = 50$ or perhaps even higher [47], [53]. Acceleration, both parallel and perpendicular to the motion of jet components, is also common [54]. In general, it is clear that gamma-ray loudness is directly related to radio properties. Gamma-ray loud jets generally have higher apparent speeds, higher Doppler factors, higher brightness temperatures, are oriented closer to the line of sight and have smaller opening angles. Jets with varying gamma-ray emission have higher apparent speeds than those with steady emission and gamma-ray bright jets are in an active radio state. There is evidence that only the energized portion of a broader underlying jet is visible [33], [55], [43], [56], [57]. The median fractional polarization (at 15 GHz) of the unresolved cores of gamma-ray emitting jets is significantly higher than for gamma-ray quiet jets [58].

5.1. High resolution followup of flaring sources
It is important to obtain high resolution observations of sources when they are flaring at high energies. As VLBI monitoring programs only observe periodically, this means Target of Opportunity type of observations are needed. This has proved to be relatively straightforward

in the northern hemisphere as the VLBA observes throughout the year. For the southern hemisphere the Australian LBA only observes for a few weeks every year which limits its ability to observe flares. To provide rapid followup to a gamma-ray flare with milliarcsecond resolution, the TANAMI program has set up a 1700 km single baseline interferometer between a 30 m dish at Ceduna, South Australia and a 26 m dish in Hobart, Tasmania. Called the Ceduna Hobart Interferometer (CHI; [59]), it can observe at most centimeter bands up to 22 GHz and provide a measure of the brightness temperature when the full TANAMI array is not available.

6. Summary

Radio observations of AGN are critical to understanding high energy emission and indeed the basic physics of these objects. Virtually all high energy AGN are radio loud and thus accessible to observations in this band. The unparalleled angular resolution afforded by interferometric techniques and the ability to probe a range of time scales means radio observations play a special, indeed unique, role in the suite of multiwavelength observations that are set to transform our understanding of AGN. This somewhat unlikely but strong symbiosis between observations at opposite ends of the electromagnetic spectrum is central to efforts to answer the fundamental outstanding questions about these objects.

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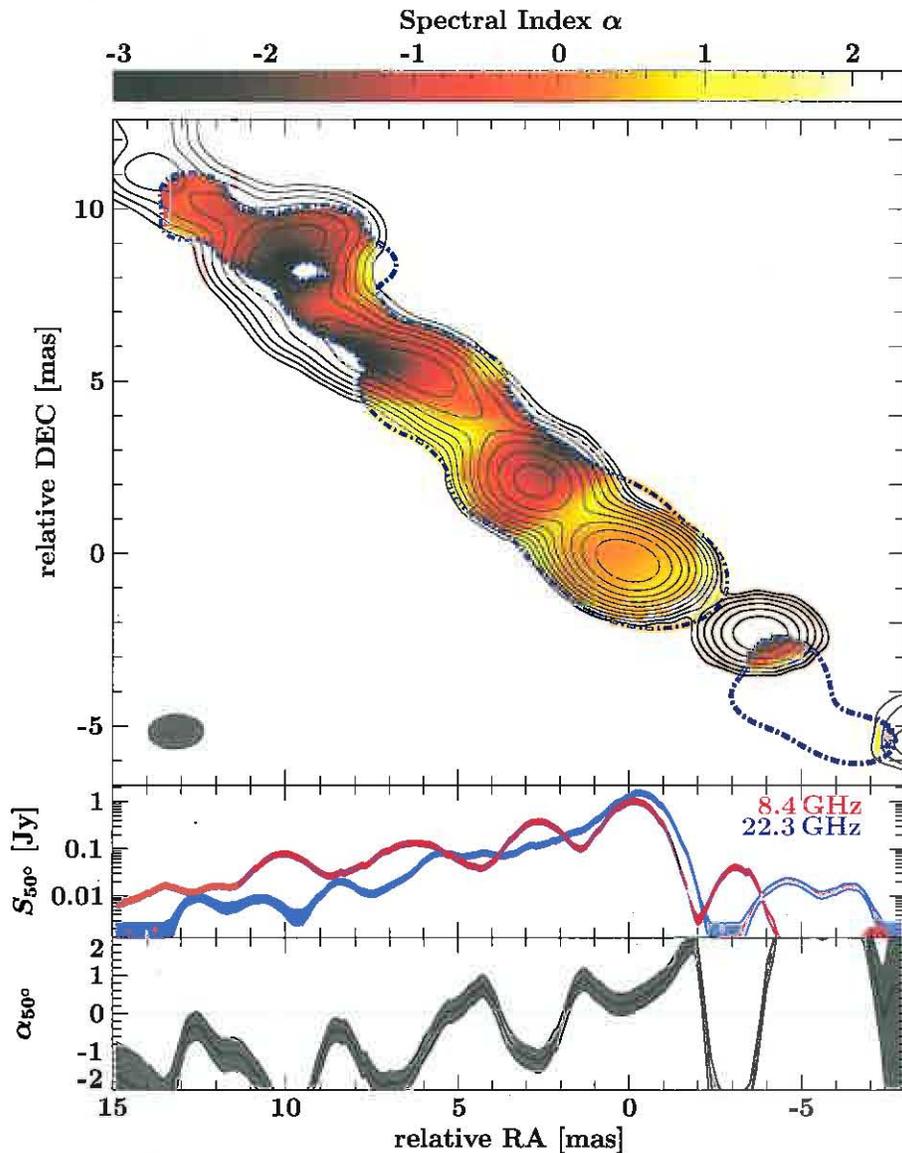
Figure 1: An example of what dual frequency VLBI imaging can reveal. Top: Spectral index map of the nearby radio galaxy Centaurus A, derived from the flux densities at 8.4 GHz and 22.3 GHz. The overlying contours show the flux density distribution at 8.4 GHz (solid black) and at 22.3 GHz (dashed gray) restored with a beam of 1.61×1.02 mas ($\theta = 88°$) represented by the gray ellipse in the lower left corner. Note that 1 mas corresponds to just 0.018 parsec at this distance. Middle: Flux density distribution at 8 GHz (red) and 22.3 GHz (blue) for a narrow strip of 0.1 mas along the jet at a P.A.=50° corrected for the shift of $\Delta\alpha \approx -0.25$ mas and $\Delta\delta \approx -0.2$ mas. Bottom: Spectral index given by the flux densities at P.A.=50°. Uncertainties corresponding to the absolute calibration uncertainties of $\sim 15\%$ and considering the image rms at both frequencies are shown as shaded regions around the best-fit distributions (solid lines). From [52].