GAMMA-RAY EMITTING AGN AND UNIFIED SCHEMES [a]

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Active Galactic Nuclei (AGN) are now known to be strong γ-ray emitters. After briefly describing the different classes of AGN and the basic tenets of unified schemes, I discuss the role of blazars (that is BL Lacs and flat-spectrum radio quasars) as γ-ray sources. The main properties of blazars and their connection with relativistic beaming are then summarized. Finally, I address the question of why blazars, despite being extreme and very rare objects, are the only AGN detected at very high ($E > 100$ MeV) energies, and touch upon the relevance of TeV astronomy for AGN research.

1 Active Galactic Nuclei

Active Galactic Nuclei (AGN) are extragalactic sources, in some cases clearly associated with nuclei of galaxies (although generally the host galaxy seems to be too faint to be seen), whose emission is dominated by non-stellar processes in some waveband(s) (typically but not exclusively the optical). One important feature of AGN is the fact that their emission covers the whole electromagnetic spectrum, from the radio to the γ-ray band, sometimes over almost 20 orders of magnitude in frequency.

It is now well established that AGN are strong γ-ray ($E > 100$ MeV) emitters. To be more specific: 1. at least 40% of all EGRET sources are AGN [7] (some more AGN are certainly present amongst the still unidentified sources) and these make up almost 100% of all extragalactic sources (the only exceptions being the Large Magellanic Cloud and possibly Centaurus A); 2. *all* detected AGN are blazars, that is BL Lacertae objects (BL Lacs) or flat-spectrum radio quasars (FSRQ).[b] To appreciate the relevance of the latter point, we will first have to tackle the subject of AGN classification.

1.1 AGN Classification

The large number of classes and subclasses appearing in AGN literature could disorientate physicists or even astronomers working in other fields. A simplified classification, however, can be made based on only two parameters, that is radio-loudness and the width of the emission lines, as summarized in Table 1 (see e.g., Urry & Padovani [30]).

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[b] The term "blazar" is here given a wider meaning than the one sometimes implied, which is restricted to highly polarized quasars (HPQ) and/or optically violently variable (OVV) quasars. The reason is that there is increasing evidence that these categories and the flat-spectrum radio quasars, which reflect different empirical definitions, refer to more or less the same class of sources. That is, the majority of flat-spectrum radio quasars tend to show

Table 1: AGN Taxonomy: A Simplified Scheme.

Radio Loudness	**Optical Emission Line Properties**		
	Type 2 (Narrow Line)	**Type 1** (Broad Line)	**Type 0** (Unusual)
Radio-quiet:	Seyfert 2	Seyfert 1 QSO	
Radio-loud:	NLRG $\left\{\begin{array}{l} FR\ I \\ FR\ II \end{array}\right.$	BLRG SSRQ FSRQ	Blazars $\left\{\begin{array}{l} BL\ Lacs \\ (FSRQ) \end{array}\right.$
	decreasing angle to the line of sight $\longrightarrow$		

Although it was the strong radio emission of some quasars which led to their discovery more than 30 years ago, it soon became evident that the majority of quasars were actually radio-quiet, that is most of them were not detected by the radio telescopes of the time. It then turned out that radio-quiet did not mean radio-silent, that is even radio-quiet AGN can be detected in the radio band. Why then the distinction? If one plots radio luminosity versus optical luminosity for complete samples of optically selected sources, it looks like there are two populations, the radio quiet one having, for the same optical power, a radio power which is about $3-4$ orders of magnitudes smaller. The distribution of the luminosity ratio L_r/L_{opt} for complete samples, including the upper limits on the radio luminosity, appears to be bimodal, with a dividing line at a value $L_r/L_{opt} \sim 10$ (e.g., Stocke et al.;[28] both luminosities are in units of power/Hz). It would therefore be better to call the two classes "radio-strong" and "radio-weak" but the original names are still used. Note that only about $10-15\%$ of AGN are radio-loud.

The other main feature used in AGN classification is the width, in case they are present, or the absence, of emission lines. These are produced by the recombination of ions of various elements (most notably H, He, C, N, O, Ne, Mg, Fe). Their width is due to the Doppler effect thought to result from more or less ordered motion around the central object. AGN are then divided in Type 1 (broad-lined) and Type 2 (narrow-lined) objects according to their line-widths, with 1000 km/s (full width half maximum) being the dividing value. Some objects also exist with unusual emission line properties, such as BL Lacs, which have very weak emission lines with typical equivalent widths (a measure of the ratio between line and continuum luminosity) < 5 Å.

As illustrated in Table 1, we then have radio-quiet Type 2 and Type 1 AGN, that is Seyfert 2 galaxies and Seyfert 1 galaxies/radio-quiet quasars (QSO) respectively. Radio-loud Type 2 AGN are radio galaxies (sometimes also called narrow-line radio galaxies [NLRG] to distinguish them from the broad-lined ones), classified as Fanaroff-Riley[5] I and II (FR I and II) according to their radio morphology (connected with their radio power), while radio-loud Type 1 AGN are broad-line radio galaxies (BLRG) and radio quasars. Finally, radio-loud sources with very weak emission lines are known as BL Lacertae objects, from the name of the class prototype, which was originally presumed to be a variable star in the Lacerta constellation.

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rapid variability and high polarization.

Concentrating on the radio-loud sources, to which most of this paper is devoted, the BLRG are, at least in my view, simply local versions of radio quasars where we can detect the host galaxy, as Seyfert 1 galaxies are local versions of QSO (the reasons why we do not see the high-redshift counterparts of Seyfert 2 galaxies are discussed by Padovani [19]). Radio quasars are generally divided into steep-spectrum radio quasars (SSRQ) and flat-spectrum radio quasars (FSRQ), according to the value of their radio spectral index at a few GHz ($\alpha_r = 0.5$ being usually taken as the dividing line, with $f_\nu \propto \nu^{-\alpha}$). This distinction reflects the size of the radio emitting region. In fact, radio emission in these sources is explained in terms of synchrotron radiation (that is radiation from relativistic particles moving in a magnetic field), which for extended regions has a relatively steep spectrum ($\alpha_r \sim 0.7$). On the other hand, nuclear, compact emission has a flatter spectrum, thought to be the result of the superposition of various self-absorbed components. The flat radio spectrum then indicates that nuclear emission dominates over the more extended emission, generally associated with the so-called "radio-lobes." In fact, flat-spectrum quasars are generally core-dominated in the radio band, that is emission from the core is much stronger than emission from the extended regions, unlike for example SSRQ or narrow-line radio galaxies which are both lobe-dominated. Note that even though FSRQ have strong broad lines they are also included in the "Type 0" column in Table 1 because their multifrequency spectra are dominated by non-thermal emission as in BL Lac objects.

1.2 Unified Schemes

All this might seem complicated, but in recent years we have developed a consistent scenario which at least explains the Type 1/Type 2 distinction. We have in fact come to understand that some classes of apparently different AGN (therefore classified under different names) might actually be intrinsically the same class of objects seen at different angles with the line of sight (see for example Antonucci [1] and Urry & Padovani [30] and references therein).

The main idea, based on various observations and summarized in figure 1, is that emission in the inner parts of AGN is highly anisotropic. The current paradigm for AGN includes a central engine, possibly a massive black hole, surrounded by an accretion disk and by fast-moving clouds, probably under the influence of the strong gravitational field, emitting Doppler-broadened lines. More distant clouds emit narrower lines. Absorbing material in some flattened configuration (usually idealized as a toroidal shape) obscures the central parts, so that for transverse lines of sight only the narrow-line emitting clouds are seen (Type 2 AGN), whereas the near-infrared to soft-X-ray nuclear continuum and broad-lines are visible only when viewed face-on (Type 1 AGN). In radio-loud objects we have the additional presence of a relativistic jet, roughly perpendicular to the disk, which produces strong anisotropy and amplification of the continuum emission ("relativistic beaming"), which I will discuss in more detail later on. For reasons still unclear, in BL Lac objects the emission lines are extremely weak, and the continuum is very strong and non-thermal (i.e., due to synchrotron and, at higher frequencies, inverse Compton emission or perhaps hadronic processes).

This axisymmetric model of AGN implies widely different observational properties (and therefore classifications) at different aspect angles. Hence the need for "Unified Schemes" which look at intrinsic, isotropic properties, to unify fundamentally identical (but apparently different) classes of AGN. Seyfert 2 galaxies have therefore been "unified" with Seyfert 1 galaxies, whilst low-luminosity (FR I) and high-luminosity (FR II) radio galaxies have been unified with BL Lacs and radio quasars respectively (see Antonucci [1] and Urry & Padovani [30] and references therein). In other words, BL Lacs are thought to be FR I radio galaxies with their jets at relatively small ($\lesssim 20 - 30°$) angles w.r.t. the line of sight. Similarly, we believe FSRQ to be FR II radio galaxies oriented at small ($\lesssim 15°$) angles, while SSRQ should be at angles in between those of FSRQ and FR II's ($15 \lesssim \theta \lesssim 40°$). Blazars are then a special class of AGN which we think have

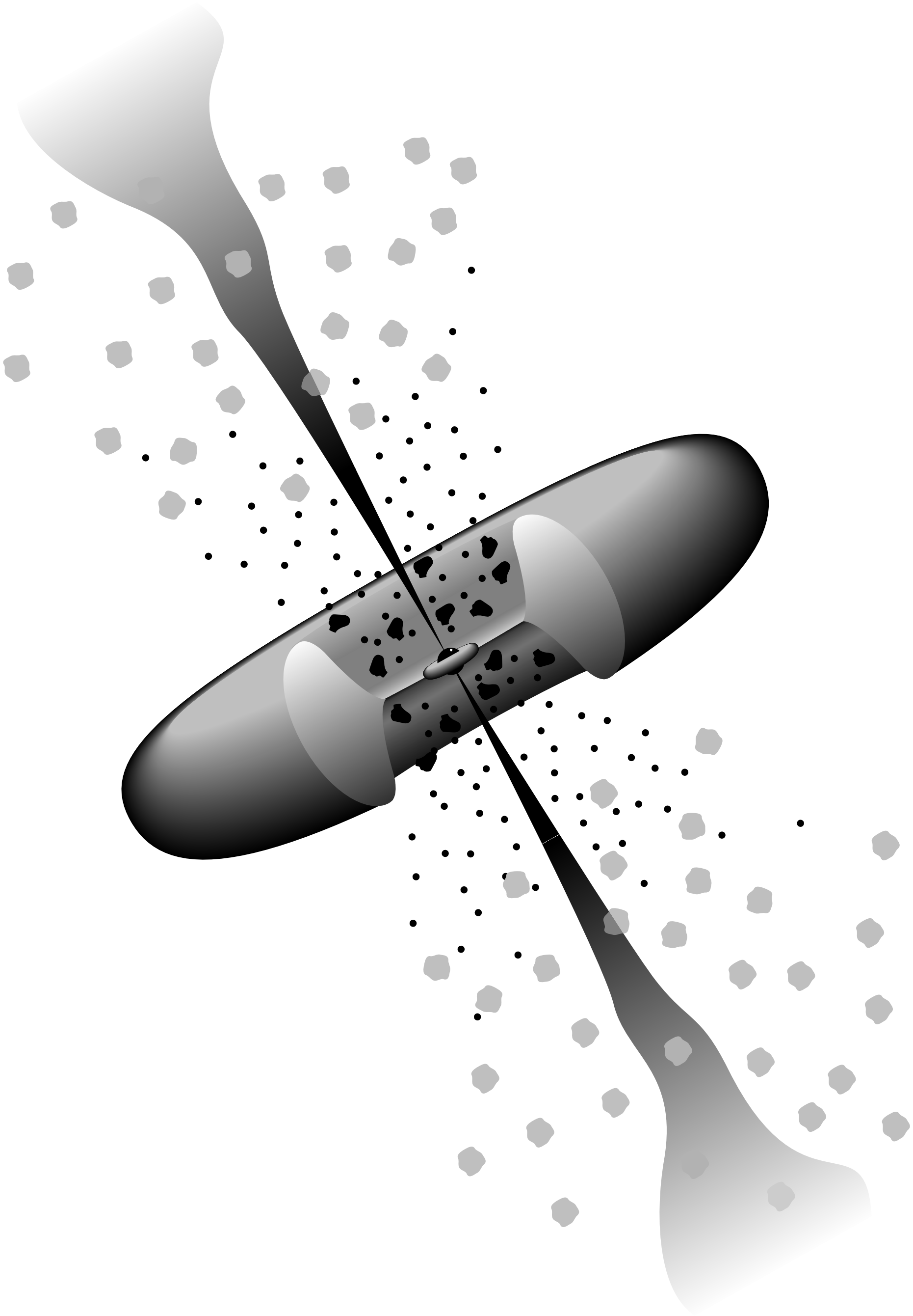

Figure 1: A schematic diagram of the current paradigm for radio-loud AGN (not to scale). Surrounding the central black hole is a luminous accretion disk. Broad emission lines are produced in clouds (dark spots) orbiting above the disk and perhaps by the disk itself. A thick dusty torus (or warped disk) obscures the broad-line region from transverse lines of sight; some continuum and broad-line emission can be scattered into those lines of sight by hot electrons (black dots) that pervade the region. A hot corona above the accretion disk may also play a role in producing the hard X-ray continuum. Narrow lines are produced in clouds (grey spots) much farther from the central source. Radio jets, shown here as the diffuse jets characteristic of low-luminosity, or FR I-type, radio sources, emanate from the region near the black hole, initially at relativistic speeds (Urry & Padovani 1995; copyright Astronomical Society of the Pacific, reproduced with permission).

their jets practically oriented towards the observer.

In general, different AGN components are important at different wavelengths. Namely: 1. the jet emits non-thermal radiation, via electromagnetic (synchrotron and inverse Compton) and perhaps hadronic processes, all the way from the radio to the γ-ray band;[12, 22] 2. the accretion disk probably emits thermal radiation, peaked in optical/ultraviolet/soft-X-ray band; 3. the absorbing material (torus) will emit predominantly in the infrared. These different components are apparent, for example, in the multifrequency spectrum of 3C 273,[10] the first quasar to be discovered and one of the best studied.

At this point one might ask: what has all this to do with γ-ray emission? The answer in the next section.

2 AGN as γ-ray Sources: the Role of Blazars

According to Unified Schemes, blazars are that special class of radio-loud AGN with their jets practically pointing towards the observer, and therefore constitute a relatively rare class of objects. Radio-loud AGN make up only $\sim 10 - 15\%$ of all AGN (e.g., Kellermann et al. [8]), while a generous upper limit to the fraction of blazars amongst radio sources is 50% (as inferred, for example, from the fraction of FSRQ and BL Lacs in the 1 Jy catalogue[27] which, being a high-frequency radio catalogue, is biased towards flat-spectrum sources). It then follows that blazars make up at most 5% of all AGN, but more likely even less than that.

Mattox et al.[14] have identified 42 high-confidence EGRET sources (mainly from the Second EGRET catalogue[29]) with AGN, all of them blazars. If the probability of detecting an AGN with EGRET were independent of the class, then in this list we would expect at maximum 2 blazars, with most sources being associated with radio-quiet AGN. Instead, we have 100% blazars and 0% other sources. In particular, no radio-quiet AGN has been detected so far by EGRET. Blazar γ-ray luminosities are in the range $10^{45} - 10^{49}$ erg/s and in many cases the output in γ-rays dominates the total (bolometric) luminosity.

To find out what is so special about blazars we need to have a closer look at their properties.

2.1 *Blazar Properties and Relativistic Beaming*

The main properties of blazars can be summarized as follows:

- radio loudness;
- rapid variability (high $\Delta L/\Delta t$);
- high and variable polarization ($P_{opt} > 3\%$);
- smooth, broad, non-thermal continuum;
- compact, flat-spectrum radio emission ($f_{core} \gg f_{extended}$);
- superluminal motion in sources with multiple-epoch Very Large Baseline Interferometry (VLBI) maps.

The last property might require some explanation. The term "superluminal motion" describes proper motion of source structure (traditionally mapped at radio wavelengths) that, when converted to an apparent speed v_{app}, gives $v_{app} > c$. This phenomenon occurs for emitting regions moving at very high (but still subluminal) speeds at small angles to the line of sight.[25] Mirabel[15] describes examples of superluminal motion in our own Galaxy.

All these properties are consistent with *relativistic beaming*, that is with bulk relativistic motion of the emitting plasma towards the observer. There are by now various arguments

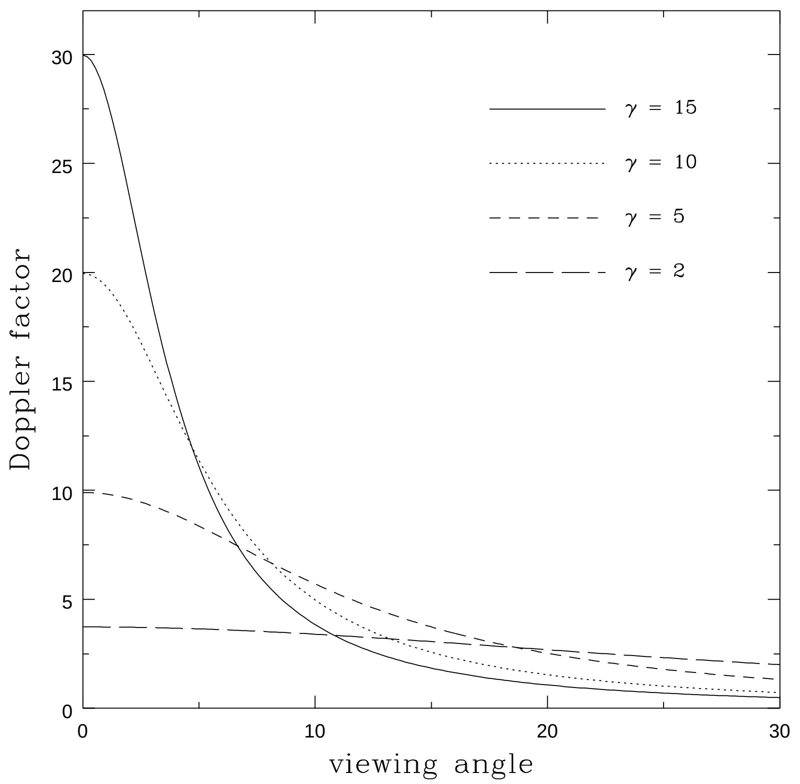

Figure 2: The dependence of the Doppler factor δ on the angle to the line of sight. Different curves correspond to different Lorentz factors: from the top down, $\gamma = 15$ (solid line), $\gamma = 10$ (dotted line), $\gamma = 5$ (short-dashed line), $\gamma = 2$ (long-dashed line).

in favour of relativistic beaming in blazars, summarized for example by Urry & Padovani.[30] Beaming has enormous effects on the observed luminosities. Adopting the usual definition of the relativistic Doppler factor $\delta = [\gamma(1 - \beta\cos\theta)]^{-1}$, $\gamma = (1 - \beta^2)^{-1/2}$ being the Lorentz factor, with $\beta = v/c$ and θ the angle w.r.t. the line of sight, and applying simple relativistic transformations, it turns out that the *observed* luminosity at a given frequency is related to the *emitted* luminosity in the rest frame of the source via

$$L_{obs} = \delta^p L_{em} \quad , \tag{1}$$

with $p = 2 + \alpha$ or $3 + \alpha$ respectively in the case of a continuous jet or a moving sphere[30] (α being the spectral index), although other values are also possible.[11] For $\theta \sim 0°$, $\delta \sim 2\gamma$ (figure 2) and the observed luminosity can be amplified by factors of thousands (for $\gamma \sim 5$ and $p \sim 3$, which are typical values). That is, for jets pointing almost towards us we can overestimate the emitted luminosity typically by three orders of magnitude. Apart from this amplification, beaming also gives rise to a strong collimation of the radiation, which is larger for higher γ (figure 2): δ decreases by a factor ~ 2 from its maximum value at $\theta \sim 1/\gamma$ and consequently the inferred luminosity goes down by 2^p. For example, if $\gamma \sim 5$ the luminosity of a jet pointing $\sim 11°$ away from our line of sight is already about an order of magnitude smaller (for $p = 3$) than that of a jet aiming straight at us.

All this is very relevant to the issue of γ-ray emission from blazars. In fact, if blazars were not beamed, we would not see any γ-ray photons from them! The qualitative explanation is relatively simple: in sources as compact as blazars all γ-ray photons would be absorbed through photon-photon collisions with target photons in the X-ray band. The end product would be electron-positron pairs. But if the radiation is beamed then the luminosity/radius ratio, which is the relevant parameter, is smaller by a factor δ^{p+1} and the γ-ray photons manage to escape from the source. More formally, it can be shown [13] that the condition that the optical depth to photon-photon absorption $\tau_{\gamma\gamma}(x)$ is less than 1 implies (under the assumption that X-ray emission arises from the same region as the γ-ray emission)

$$\delta > C \left(\frac{L_{48}}{\Delta t_d}\right)^{1/(p+1)} \left(\frac{x}{10^4}\right)^{\alpha_x/(p+1)} \quad , \tag{2}$$

where $L_{48} \equiv L_\gamma/(10^{48}$ erg/s), Δt_d is the γ-ray variability time scale in days (which is used to estimate the source size), $x \equiv h\nu/m_e c^2$, α_x is the X-ray spectral index, and C is a numerical constant ≈ 10. In other words, transparency for the γ-ray photons *requires* a relatively large Doppler factor for most blazars [4] and therefore relativistic beaming.

3 The Importance of Being a Blazar

We can now address the main question of this paper: why have blazars been detected by EGRET? There are, I believe, at least three reasons, which have to do with the fact that blazars are characterized by:

1. high-energy particles, which can produce GeV photons;
2. relativistic beaming, to avoid photon-photon collision and amplify the flux;
3. strong non-thermal (jet) component.

Point number one is obvious. We know that in some blazars synchrotron emission reaches at least the optical/ultraviolet range, which reveals the presence of high-energy electrons which can produce γ-rays via inverse Compton emission (although hadronic processes can also be important or even dominant [12]). Point number two is vital, as described in the previous section, not only to enable the γ-ray photons to escape from the source, but also to amplify the flux and therefore make the source more easily detectable. Point number three is also very important. γ-ray emission is clearly non-thermal (although we still do not know for sure which processes are responsible for it) and therefore related to the jet component. The stronger the jet component, the stronger the γ-ray flux.

Having understood why blazars have been detected by EGRET, one could also ask: why have not *all* blazars been detected? Many blazars with radio properties similar to those of the detected sources, in fact, still have only upper limits in the EGRET band. This problem has been addressed, for example, by von Montigny et al., [16] who suggest as possible solutions variability (only objects flaring in the γ-ray band can be detected) or a γ-ray beaming cone which either points in a different direction or is more narrowly beamed that the radio one (see also Salamon & Stecker [26] and Dermer [3]). These can certainly be viable explanations, but one should also note that even a moderate dispersion in the values of the parameters required for γ-ray emission described above (particle energy, Doppler factor, and non-thermal component strength) can easily imply the non-detection of some sources and the detection of others with similar radio properties.

Do the points discussed above also explain why EGRET has not detected any of the more numerous radio-quiet AGN? Yes, although not all of them might be essential in this case. As radio-emission (at least in radio-loud AGN) is certainly non-thermal, while the optical/ultraviolet emission might be thermal emission associated with the accretion disk (at least in radio-quiet AGN), then the ratio L_r/L_{opt} could actually be related to the ratio $L_{non-thermal}/L_{thermal}$. Furthermore, L_γ seems to scale with L_r, although the details of this dependence are still under debate (see e.g., Mattox et al.[14] and references therein). It could then be that even radio-quiet AGN are γ-ray emitters, although scaled down by their ratio between radio and optical powers, that is at a level $3-4$ orders of magnitude below that of blazars, with typical fluxes $F_\gamma \approx 10^{-10}$ photons cm^{-2} s^{-1}. In other words, radio-quiet AGN would fulfill requirements number one and two[c] but not number three.

Alternatively, it could be that for some reason the emission mechanisms at work in radio-loud sources are simply not present in the radio-quiet ones, either because there is no jet at all in radio-quiet AGN or because, for example, there is no accelerating mechanism. In this case, either condition number one or number three (or both) would be missing (number two would now be unimportant), and no γ-ray emission would be expected.

Unfortunately, it is not going to be possible to test these two alternatives on the basis of γ-ray data for some time: even in the first case, in fact, the expected γ-ray fluxes are below the sensitivity of currently planned future γ-ray missions, like GLAST.[17]

4 AGN as TeV Sources

So far, only emission up to a few GeV has been considered. However, TeV astronomy is now in full swing, as we have heard at this meeting, and it is therefore interesting to consider the situation at these energies.

Two, possibly three, extragalactic sources have been detected at $E > 0.3$ TeV;[32] these are all BL Lacs. That is, even at energies above those of EGRET (and exactly for the same reasons) the only γ-ray emitting AGN are still blazars! The difference here is that, unlike the situation in the EGRET band where the majority of detected blazars are flat-spectrum radio quasars, only BL Lacs have been detected so far. Furthermore, these BL Lacs are the three nearest confirmed BL Lacs in the recent catalogue by Padovani & Giommi,[21] namely MKN 421 (redshift $z = 0.031$), MKN 501 ($z = 0.055$) and 1ES 2344+514 ($z = 0.044$), the latter needing confirmation to be considered a firm detection. The fact that only relatively nearby BL Lacs have been detected is probably related to absorption of TeV photons by the infrared background (see e.g., Biller[2] and references therein).

Why have no flat-spectrum radio quasars been detected at TeV energies? These sources are typically at higher redshifts and so the effect on them of the cosmological absorption by infrared photons is more severe. However, there are at least four strong radio sources classified as flat-spectrum quasars at $z < 0.1$, including 3C 120 and 3C 111, the latter having been looked at by the Whipple experiment, with negative results.[9] (3C 111, however, although superluminal,[31] is lobe-dominated [$f_{core}/f_{extended} \simeq 0.2$[6]], which suggests it is an unlikely blazar. Also, it has not been detected by EGRET.)

This is certainly small number statistics and definite conclusions should only be drawn after a larger number of relatively local flat-spectrum radio quasars have been observed at TeV energies. However, the non-detection of flat-spectrum radio quasars could simply mean that *internal* absorption is significant in these sources. In fact, the cross-section for photon-photon interaction for ~ 1 TeV photons is maximum at $\sim 10^{14}$ Hz or $\sim 2.5\mu$ and quasars have a larger photon density than BL Lacs at these frequencies, be it emission from the obscuring torus[d] or even the accretion disk (see e.g., Protheroe & Biermann[23]).

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[c]One could argue that the relativistic beaming requirement would probably not be very important in radio-quiet AGN as the luminosity/radius ratio in the γ-ray band in these sources would be much lower anyway and γ-ray photons would escape even without beaming. However, GeV photons collide preferentially with X-ray photons, which are plentiful in these sources: some beaming might then be required for the (putative) γ-ray emission in radio-quiet AGN as well.

[d]It is not clear if the presence of an obscuring torus is required in BL Lacs as well as in radio quasars: see discussion in Urry & Padovani[30] and Padovani[20] and references therein.

The new, more sensitive projects which are underway in the field of TeV astronomy [24] will certainly shed light on these issues. Furthermore, the detection of (necessarily local) AGN at $E > 10$ TeV would essentially rule out leptonic models (i.e., inverse Compton emission by electrons) and turn the balance in favour of hadronic processes being responsible for the γ-ray emission in these sources. [12] These so-called "proton blazars" would also be strong neutrino sources [33] possibly detectable by the large, high-energy neutrino experiments discussed at this meeting. [18]

5 Summary

The main conclusions are as follows:

1. The only AGN detected at GeV (EGRET) and even TeV (e.g., Whipple) energies are blazars, that is a special class of sources which includes BL Lacertae objects and radio quasars with a relatively flat radio spectrum. These sources are thought to have their jets moving at relativistic speeds almost directly towards the observer, a phenomenon which goes under the name of "relativistic beaming" and causes strong amplification and collimation of the radiation in our rest frame.

2. As blazars make up *at most* 5% of all AGN, they must have some peculiar characteristics which favour their γ-ray detection. I have shown that relativistic beaming plus a strong non-thermal (jet) component play, in fact, a fundamental role in making these sources detectable at γ-ray energies.

3. γ-ray missions $\sim 1,000$ times more sensitive than EGRET (that is, below the sensitivity of presently planned missions like GLAST) might also detect the bulk of the more common radio-quiet AGN, under the assumption that they also possess, on much smaller scales, a non-thermal engine.

4. TeV astronomy, a very young branch of astronomy which has already produced some very exciting results, will likely play an important role in the near future in constraining blazar models.

In summary, there exists a tight connection between unified schemes and γ-ray emission in AGN, as they both depend on relativistic beaming, the former as a mechanism to produce a strong angle dependence of the observed properties, the latter as a way to let γ-ray photons escape from the source.

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