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AGN unification scenarios : the case of the radiogalaxy M87

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The radiogalaxy M87 is the first non-blazar extragalactic source detected at very high energies by Cherenkov telescopes. It questions our global understanding of TeV emission of active galactic nuclei (AGN) and may shed new light on our general view of AGN physics and unification.

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1. Introduction

First detected at Very High Energies (V.H.E.) by the HEGRA experiment [1], the radiogalaxy M87 was later confirmed as TeV source by the H.E.S.S. Cherenkov array, which also revealed fast variations on the time scale of days [2]. Both findings were recently strengthened by MAGIC and VERITAS which observed TeV variations of M87 in January 2008 [3-5].

Thus M87 is the first non-blazar extragalactic source to be detected in the V.H.E. range. It questions our global understanding of TeV emission scenarios for AGN, and to some extent our general view of AGN classification.

2. AGN unification schemes

The main goal of AGN unification is to identify a small number of fundamental parameters which would characterize the different types of AGN. Parameters such as the central black hole mass M_{BH}, the accretion rate, and the viewing angle ψ, have been proposed. The black hole spin J_{BH} may have a significant influence on radio-loudness. Others parameters related to environment, evolution and feedback effects could also be important to complete the picture [6,7].

2.1. The standard unification model

In the radio-quiet case, the classification of AGN according to their viewing angle has been quite successful. It describes Seyfert 1 nuclei (and their powerful counterpart, the QSO) as AGN seen mainly face-on or at limited angles from their central axis, while Seyfert 2 nuclei are seen edge-on through the equatorial disk and dusty torus. In the radio-loud case, which concerns 10 % of all AGN and 50 % of the brightest ones, blazars such as BL Lac objects and powerful FSRQ (Flat Spectrum Radio Quasars) are seen at very small angles relatively to their radio jet, while radio quasars, and FR I /FR II radiogalaxies are seen at increasing viewing angles.

However the major dichotomy among AGN, namely the radio-loud and the radio-quiet objects, is not yet fully understood. The so-called ‘radio-loud’ sources have well developed and collimated radio jets. The transition between the two families should correspond to a transition between jet and wind solutions for outflows from compact objects. Indeed poorly collimated outflows are clearly found in ‘radio-quiet’ AGN, as shown for instance by warm absorbers and ionized winds observation. The value of the spin of the black hole (or of the accretion disk) may induce or not the jet formation by modifying initial conditions at the base of the outflow. J_{BH} is often quoted as the dominant parameter explaining the radio dichotomy. Alternatively, the properties of the ambient interstellar gas can also modify the propagation of the outflow and fix its characteristics as jet or wind. Such explanation of the dichotomy is suggested by the striking property, known since many years but firmly confirmed by deeper investigation, that radio-quiet

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AGN are found in disk galaxies and radio-loud ones in elliptical galaxies [8]. A third possibility, which seems to gain an increasing support, combines both effects (black hole spin and environment) by considering a universal link between the AGN and host galaxy properties.

2.2. AGN unification versus formation and evolution of Galactic Nuclei

There are growing evidences for a strong relation between AGN and their host galaxy evolution. Independent teams have firmly established a clear correlation between the mass of the central black hole and of the galactic bulb, such that $M_{BH} \sim 0.002\ M_{bulb}$ [9-11]. This suggests a common formation of the supermassive black holes (SMBH) and the host galaxies. Another result shows a difference in the stellar content in the circumnuclear region of Seyfert 1 and Seyfert 2 galaxies, more young stars being found in Seyfert 2. Clues for a correlation between circumnuclear starbursts and activity of the nuclei have been found. These findings can not be explained in the standard classification by viewing angle and suggests a sequence of evolution between the different types of AGN [12, 13].

Furthermore, it is now known that a large fraction of non-active galaxies harbours a SMBH. Indeed Seyfert nuclei are not numerous enough to host all quasars remnants. The luminosity function of quasars in X-rays for different redshifts shows that there is an evolution both in luminosity and in number [14]. The number of luminous quasars has a maximum around $z \sim 2\text{-}3$, while the total number of quasars is found maximal around $z \sim 1$. Numerical experiments illustrate how major events during the lifetime of a normal galaxy such as collision and merger can initiate a main activity phase of its galactic nucleus [15, 16]. All these results are coherent with the presence of dead quasars and passive SMBH found in low-redshift normal galactic nuclei.

Feedback effects, namely the influence of the AGN and jets on their galactic environment (host galaxies, galaxy clusters and cooling flows), come in addition to reinforce the link between galactic nuclei and host galaxies. Simulations of the large scale environment (~300 kpc) of M 87 for instance, successfully describe the evolution of its halo and cooling flow over 12 Gyr with an accretion peak at 0.2 $M_{\odot}$/yr, inducing a feedback by the jets, and the stabilization of the cycle at an accretion rate of 0.006 $M_{\odot}$/yr [17].

A global scenario of the co-evolution of AGN and galaxies has been proposed as follows. Hierarchical growth of structures and mergers of galaxies induce large scale inflow of the interstellar and intergalactic gas towards central regions of the galaxy, which results in circumnuclear starbursts, growth of central SMBH and activity of nuclei, quasars and AGN. Then feedback effects from the AGN slow down, or even stop the inflow, and the galaxy evolves into a normal ‘non-active’ galaxy or a dead quasar. Eventually a new merger event may restart the cycle [15]. Such views are still under debate but illustrate how much activity of galactic nuclei can be linked to galaxy evolution.

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3. The blazar family

What is the place of the blazar family in this "big picture"? Blazars, which correspond to a very specific orientation towards us, are relatively rare. Available surveys of blazars suffer several biases. Furthermore, the strong and complex effects due to Doppler boosting come in addition to complicate the situation.

However V.H.E. emission is up to now detected mainly from blazars, and TeV observations perfectly disentangle non-thermal effects from thermal ones possibly present at others wavelengths. Gamma ray observations thus allow a privileged view on AGN jets. Model-dependent fits of the spectral energy distribution (SED) of gamma AGN provide interesting constraints on the jet physics [18]. New significant data should come soon, especially with GLAST to analyse the MeV-GeV emission of BL Lac objects, still poorly known. It will shed new light on the blazar population. So, despite their rareness and peculiarities, blazars clearly deserve deeper analyses.

3.1. The blazar sequence

The so-called 'blazar sequence' has been first established from the average SED deduced from a sample of 126 blazars binned according to their radio luminosity L_{radio} [19]. These SED were shown to present two bumps with correlated peak frequencies. Most luminous sources appeared to peak at lower frequencies ν_{peak}, and the luminosity ratio between high and low frequency bumps to increase with bolometric luminosity. This was interpreted as a continuous sequence from the most powerful FSRQ, through LBL (Low-frequency peaked BL Lac objects), to the weaker HBL (High-frequency peaked BL Lac objects). A unifying scheme based on leptonic models proposed to ascribe the low-energy bump to synchrotron emission, and the high-energy bump to inverse-Compton emission, both synchrotron-self-Compton (SSC) and external Compton (EC), the relative importance of EC decreasing from FSRQ to HBL [20]. Such scenario was able to reproduce the sequence when varying the radio luminosity as a free parameter.

3.2. New perspectives on the blazar sequence

In recent years, new data and deep survey analyses questioned the validity of the first blazar sequence [21-23]. The anticorrelation between L_{radio} and synchrotron peak frequency ν_{peak} was not confirmed. Moreover, the existence of both 'low L – low ν_{peak}' and 'high L – high ν_{peak}' objects was discovered, as well as a new class of FSRQ with synchrotron peaks in the UV/X-ray range. Contrary to the prediction of the first blazar sequence, the sub-class of HBL sources appeared to represent only about 10 % of the BL Lac population [23].

One important property seems to remain from the original blazar sequence, the fact that powerful FSRQ do not reach the frequency peak of BL Lac objects, their maximum synchrotron peak frequency remains 10 to 100 times smaller. However, there are still growing evidences that

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not all objects fit the trend found in 1998. Selection effects which were difficult to take into account may explain this evolving situation. Alternatively, the apparent anticorrelation between the luminosity and the synchrotron peak frequency ν_{peak} can be an artifact of Doppler boosting [24].

This new revisited blazar sequence can be successfully reproduced by a scenario modeling all blazar SED as a function of two parameters, the black hole mass and the accretion rate [25]. Black hole masses are typically between 10^8 and 10^{10} $M_\odot$. The disk luminosity of all blazars is sub-Eddington, with $L_{disk} < 3 \times 10^{-3} L_{Edd}$ for BL Lac objects. Future statistical studies, especially in the gamma-ray range with GLAST and CTA, will show whether a blazar can indeed be characterized by only two parameters, or if additional parameters such as black hole spin, viewing angle, or environment factors have to be taken into account.

4. The radiogalaxy M 87 : scenarios for TeV emission

Current modelling of the TeV emission of blazars needs a strong Doppler boosting to account for the high and variable V.H.E. gamma-ray fluxes. Doppler factors between 20 and 50 are usual in standard one-zone SSC models [26]. Values up to 100 may be required to explain fast variations detected in the BL Lac PKS 2155-304 [27]. Such high Doppler boosting is consistent with the general description of blazars as AGN with relativistic jets directly pointing towards the Earth. However the detection of the radiogalaxy M87 at TeV energies brings a new problem since its large scale jet is not highly beamed towards us, with a viewing angle $\psi \sim 20°$ which allows only moderate Doppler factors.

Furthermore, even assuming a high Doppler factor, the TeV variability of M 87 requires very small emitting zones, of the order of a few Schwarzschild radii of its 3×10^9 $M_\odot$ black hole, under causality argument [2]. This raises the critical question of particle acceleration mechanisms in such small regions, and excludes the Virgo cluster, the radio lobes, the host galaxy, the large scale jet and its brightest knot A as TeV emission zone. Three different emitting zones can still be considered, the peculiar knot HST-1 located at about 65 pc from the nucleus, the inner VLBI jet, and the central engine itself, in the close vicinity of the black hole [28-30].

4.1. HST-1 scenario

The knot HST-1 can be described as a recollimation shock. It is known to show superluminal motion, with apparent speeds up to 4c [31], which corresponds to a moderate Doppler boosting. Inverse Compton effect on background infrared and optical photons by electrons producing the X-ray flares in a magnetic field B of the order of 1 mG can explain the TeV fluxes [32]. One difficulty is that the recollimation has to be extremely efficient to reach a size small enough to allow the observed fast variations. Support to this model came from the coincidence of increasing X-ray flux of HST-1 and TeV maxima in 2005 [33]. However the X-ray light curve of HST-1 obtained by CHANDRA in 2008 does not follow the TeV one, as recently shown by VERITAS [3,4]. This last result now seems to favour scenarios with TeV emission coming from the core of M87, namely from inner jet or central engine.

4.2. Inner jet scenarios

Two types of inner jet scenarios, adapted from standard TeV emission models for HBL, have been recently proposed. A spine-layer scenario assumes a structured jet with two components, a fast core emitting radio to X-ray and GeV photons, surrounded by a slower sheet emitting TeV photons, which can dominate the emission at large viewing angles [34]. Combined SSC and EC emission from the spine and the layer provide the ingredients to give account for the observed SED for a viewing angle of the order of 18°. Typical values of the magnetic field and the Lorentz factor are B ~ 1 G (resp. 0.3 G) and Γ ~ 12 (resp. 4) in the spine (resp. layer). Particle acceleration can be due to turbulence in the layer. This model is not very constrained since there are two sets of free parameters, in the spine and in the layer. However it reproduces the SED of a LBL, namely BL Lac itself, when seen at smaller viewing angle of about 6°.

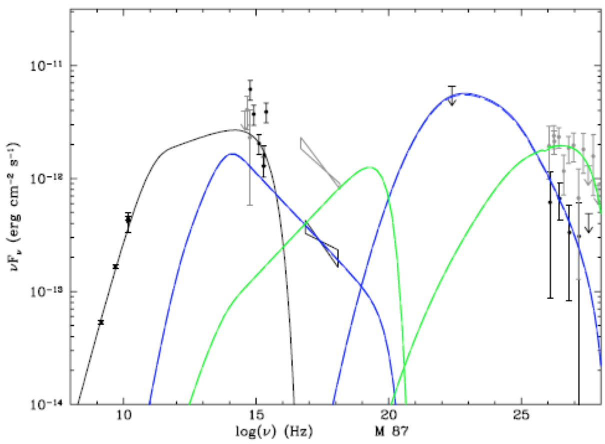

Fig. 1 : *Two different states of the SED (blue and green) can be generated within the multi-blob SSC scenario to reproduce the V.H.E. spectra obtained by HESS for high and low activity levels of M87 (from Lenain et al, 2008 [35]).*

Another scenario, the multi-blob SSC model, considers that the emission zone is located in the jet formation region, at about 50 to 100 Schwarzschild radii R_s from the central SMBH, close to the jet Alfven surface. There the jet has a somewhat large opening angle, resulting in a differential Doppler boosting in the emitting zone. Particle acceleration can occur in shocks inside the jet [35]. As shown in Fig.1, SSC emission from broken power-law electron distribution satisfactorily reproduces the observed SED for both high and low gamma-ray states, with macroscopic parameters of the inner jet consistent with values obtained by GRMHD simulations of the M87 jet [36], with typically B ~ 10 mG at $100R_s$ and Lorentz factor Γ ~ 10 for the low state, and a jet viewing angle of ~ 15°.

In addition to future gamma data with GLAST and CTA, clues and tests for such inner jet models are also expected from on-going efforts and future VLBI observations [30]. Since one mas corresponds to 300 R_s in the case of M 87, VLBI can resolve and probe the core region down to the 100 R_s scale, studying in details its structure and dynamics.

4.3. Core scenarios : TeV emission from close surroundings of the black hole

Two interesting sites for particle acceleration can be identified while following the accretion-ejection flow in the close vicinity of the central SMBH, namely the accretion disk and the black hole magnetosphere [37]. Stochastic acceleration can for instance easily occur in turbulent low-luminosity disks when proton-photon interaction can be neglected. Such mechanism is very efficient for protons which can reach the range of 10^{17} to 10^{19} eV, but not for electrons due to heavy synchrotron losses. It naturally provides power law particle distributions. Different assumptions can also result in efficient particle acceleration inside disks [38-40]. Fast particles then escape from the accretion disk and can be further accelerated by centrifugal force or in gaps in the corotating black hole magnetosphere [37,41-45]. For values of physical parameters expected in M87, electrons can then reach 10 to 100 TeV, and protons about 10^{20} eV. Both types of particles are therefore potentially radiating in the V.H.E. range.

This kind of views suggests that we finally observe a mixture of hadronic and leptonic emission. Stochastic acceleration of protons is likely a slower varying process and may be related to ‘quiet’ or ‘stationary’ TeV components. Conversely, centrifugal acceleration is a direct acceleration mechanism, namely a faster process possibly related to highly variable events.

In the case of centrifugal acceleration, the size of the acceleration and emitting zone is of the order of the light cylinder radius $R_L = c/\Omega^F$ of the black hole magnetosphere, where the azimuthal speed of the corotating magnetic structure reaches the speed of light. R_L is typically of the order of a few R_s for black holes with intermediate rotation, $0 < J_{BH} < J_{max}$, so such acceleration mechanism applies to black holes with intermediate spin. This appears coherent with the value $J_{BH}/J_{max} > 0.65$ deduced in M87 from the optical depth of ADAF (Advection Dominated Accretion Flow) radiation field to TeV photons [46]. It is often believed that central black holes of radio-loud sources correspond to states of maximal rotation. However, moderate rotation can be expected for instance for black holes fed by chaotic accretion [47], or when an efficient Blandford-Znajek process is at work, or for accretion-ejection solutions with a significant angular momentum carried out by the jet.

The SED of M87 have been reproduced by considering the synchrotron and curvature radiation, and inverse-Compton emission of ultrarelativistic electron-positron pairs on soft photon background, taking into account the electromagnetic cascades via pair production [44].

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Inverse-Compton upscattering of ADAF disk photons by centrifugally accelerated particles is an appealing possibility [45].

5. Implication on AGN unification

The detection and monitoring of M87 in the V.H.E. range have already motivated several new proposals for particle acceleration mechanisms around black holes, which have now to be tested. A large variety of plausible emitting zones and radiation processes is also envisaged. They may be related to various variability states, or possibly to various types of sources. Further statistical analyses and monitoring of AGN samples at very high energies will tackle these still open questions. A significant step forwards will be to firmly detect and study quiescent stationary V.H.E. states between active flares of AGN. At present time, this appears possible only for a few bright sources as the BL Lac PKS 2155-304. Dealing with real stationary fluxes will at last allow a good statistical approach of gamma-ray AGN samples, by comparing objects in the same activity state. This will become possible with GLAST, and at the highest energies, with the advent of large Cherenkov arrays of the next generation as CTA. At the present moment, we can just try to extrapolate some outcomes of the different scenarios elaborated for M87.

5.1. Inner jet scenarios

Proposed inner jet scenarios modify the radiating emitting cones and consider that V.H.E. emission beams have a larger opening angle than the global VLBI and large scale radio jets. This is somewhat reminiscent of a previous scheme for unifying X-ray and radio-selected BL Lac, found at that time coherent with the statistics of the BL Lac population [48]. Larger jet opening angles also help to reconcile the absence of superluminal motion in radio VLBI and high Lorentz factors required by TeV emission models [49-51]. Further developed for the radiogalaxy M87, but from standard leptonic models for HBL, these new scenarios should likely apply as well to other beamed sources such as the two LBL detected in the V.H.E. range, BL Lac [52] and W Comae [53], and the blazar 3C279 [54]. Considering that HBL represent a small fraction of the BL Lac population (10%), one can propose a classification of TeV emitting AGN by slightly increasing viewing angles, from HBL seen strictly along the jet ($\psi \leq 3°$), to LBL ($\psi \sim 6°$), and FRI radiogalaxies ($\psi \geq 10°$). Radial structure in jet formation zone may account for part of the differences in observed fluxes, spectra and light curves. Future data of high energy and V.H.E. astronomy will soon allow to confirm or to dismiss these proposals.

5.2. Core scenarios

Scenarios of V.H.E. emission from the core require several conditions in the central engine. From optical depth arguments, the accretion regime has to correspond to an ADAF or to the more general case of a RIAF (Radiatively Inefficient Accretion Flow). Stochastic acceleration of hadrons in the disk needs a turbulent RIAF. Acceleration of particles in the

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corotating black hole magnetosphere is not efficient for Schwarzschild black holes, nor for black holes at maximal rotation. A non-zero but not maximal black hole spin is needed. If radio-loudness is indeed exclusively linked to maximal black hole spins, this means that this last acceleration mechanism can be possibly more efficient in radio-quiet sources. V.H.E. emission would therefore be expected also from radio-quiet sources. Under such circumstances, TeV data may even reveal apparently "dormant" SMBH.

Possible tests of such core scenarios may come right now when trying to apply them to already available data on HBL, to check whether the proposed acceleration mechanisms are able to generate the required energetic particle distribution, for instance during the extremely active state of PKS 2155-304 monitored by HESS in 2006 [27], which also requires a very small emitting zone of a few Schwarzschild radii in size.

If their true existence is confirmed, the mechanisms analysed by the core scenarios open several interesting perspectives. First, they mean that V.H.E. data probe the very central engine and can shed new light on ambient radiation field, accretion regime, jet formation and various acceleration processes in close black hole surroundings. Secondly, they show that "dormant" but rotating SMBH can still accelerate particles, as previously proposed [55-58]. Such results bring important issues related to the origin of extragalactic cosmic rays, and recent and still debated AUGER results [59]. They may offer an explanation to the correlation claimed by AUGER between the arrival directions of the most energetic cosmic rays and the spatial distribution of low redshift AGN, which mainly involves apparently weak AGN. In such a case, UHECR data would provide a new and original way to directly analyse the evolution of AGN towards 'dead AGN' and 'quiescent' galactic nuclei.

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