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# Radio Galaxies at TeV Energies: Preface

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**Abstract:** The majority of the known extragalactic sky from TeV gamma-ray energies consists of blazars having plasma jets pointing in the direction of the line-of-sight, which results in a large Doppler boosting of their emission. Up to now, only six galaxies with a larger viewing angle have been detected in the TeV range. These objects also show fascinating properties, such as fast variability or spectral features and are called "radio galaxies". The TeV radio galaxies provide a unique laboratory for studying key aspects of active galactic nuclei. This Special Issue of *Galaxies* targets these exciting objects.

**Keywords:** active galactic nuclei; radio galaxies; emission: non-thermal; gamma-rays

## 1. Introduction

The jets of the majority of gamma-ray detected active galactic nuclei (AGN) are observed under very small angles between the jet-axis and the line-of-sight. Those objects are called blazars, an abbreviation for "blazing quasi stellar object". Due to the motion of the particles in the jet close to the speed of light, the radiation coming from blazars is strongly Doppler boosted. The frequently observed rapid variations of the brightness of these objects are related to larger, time-dilated emission regions. Instead, radio galaxies are being viewed under larger angles and the Doppler boosting of the flux is only moderate or negligible. For this reason almost all detected gamma-ray AGN are viewed under a small angle, because the amplification of the flux leads to a higher detection probability. It is also the reason why it was originally believed that blazars are the only objects that are detected in the gamma-ray band and which show flux variations. However, observations in recent years with the Fermi Large Area Telescope and imaging air Cherenkov telescopes have revealed that radio galaxies show similar variability time scales as blazars, which limit the theoretical models for particle acceleration and the emission, e.g., [1–3]. Furthermore, in case of a weak Doppler-boosted emission from an AGN jet with larger viewing angle, additional emission components may become visible.

So far, 78 individual AGN were detected by ground-based gamma-ray instruments until December 2019 in the very-high-energy (VHE) gamma-ray range between a few tens of GeV up to about 100 TeV. All but six of these objects are blazars. The non-blazar AGN are: Centaurus A, M 87, NGC 1275, IC 310, PKS 0625−354, and 3C 264.

## 2. Summary of the Contributions

The present issue contains a general review by Rieger and Levinson with a summary of the observed characteristics of all radio galaxies in the VHE band together with a recap of state-of-the-art theoretical models for the gamma-ray emission in AGN [4]. A dedicated article by Hirotani reviews the production of VHE emission in the magnetosphere close to rotating black holes [5]. Perucho

summarizes the conditions under which dissipative processes of magnetic or kinetic energy in relativistic jets occur and describes their role in the evolution of AGN jets and propagation [6]. Rani reviews combined radio and gamma-ray observations with special emphasis on the properties of TeV detected radio galaxies [7]. Such studies are crucial for the understanding of the location of gamma-ray emission sites jets of AGN in general.

Centaurus A is one of the best studied extragalactic objects in general and is located at a distance of ∼3.7 Mpc. The energy spectrum in the GeV to TeV band of Centaurus A shows an usual hardening at higher energies, indicating a new gamma-ray component connected with the high energy emission. So far, no flux variations were measured from Centaurus A in the gamma-ray band. For this issue, Davids et al. performed a correlation study of long-term light curves in the high-energy gamma-ray and X-ray band using *Fermi*-LAT and *Swift*-BAT data [8].

NGC 1275, also known as 3C 84, is the central galaxy of the Perseus cluster of galaxies. The sub-parsec radio jet shows a new component which appeared about ten years ago and keeps growing in brightness as it moves along the jet. In late 2016 to beginning of 2017, NGC 1275 showed an extremely bright and fast VHE outburst that was fifty times brighter than previously reported measurements. One research article in this issue by Britzen et al. [9] investigates high-resolution very-long-baseline-interferometry data of NGC 1275 and studies the correlation of the parsec-scale images of the jet with the flaring VHE emission behavior.

All detected non-blazar AGN show a Faranoff–Riley type I (FR I) radio morphology on kilo-parsec scales with jets ending in diffuse "edge darkened" plume-like structures. Baldi et al. examined for this issue the possibility of the detection of FR 0 radio galaxies in the VHE band, low-power radio galaxies with limited jet structures [10]. They review the results on the discovery of the FR 0 radio galaxy Tol 1326−379 in the gamma-ray band with *Fermi*-LAT.

This special issue contains a sample of articles that effectively summarize the main aspects of TeV detected radio galaxies from the observational, theoretical, as well as simulation point of view, highlights some individual objects, and discusses a possible new class of gamma-ray loud radio galaxies.

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