Extragalactic jets in the SKA era: solving the mystery of Ultra High Energy Cosmic Rays?

Sara Turriziani[*][†]

University of Rome Tor Vergata

E-mail: sara.turriziani@roma2.infn.it

The extreme properties shown by supermassive black holes at the centres of galaxies (active galactic nuclei; AGN) make them obvious candidates for producing Ultra High Energy Cosmic Rays (UHECRs), the most energetic particles known in the Universe.

AGN can exhibit outflows in the form of powerful, collimated jets of particles, accelerated in some cases close to the speed of light. Although AGN jets dimension and magnetic field could in principle accelerate particles to extreme energies, it is not easy to develop a model which describes an efficient acceleration mechanism. Different solutions have been proposed, but they need further investigation from both observational and theoretical point of view: in fact, two pieces of astrophysical understanding would need revision, namely the parameters (size and magnetic fields) in jets of AGN, and the strength of the magnetic field in the local region of the Universe.

The capabilities offered by the Square Kilometre Array (SKA) in improving current measures of the jet physical parameters will permit a better characterization of the magnetic field strength ,and its structure within the jet itself. This will be crucial to refine our estimations for the key parameters of the nearby γ-ray AGN, which are to date the best candidate sources of UHECRs.

---

[*]Speaker.

1. Introduction

In 2002, the U.S. National Research Council's Committee on Physics of the Universe composed a list of 11 particularly direct questions about the cosmos. "Where do ultra-energy particles come from?" is one of these fundamental but still unanswered questions. After many decades of investigation, this fascinating enigma is still attracting several theoretical efforts, as there are severe limitations to the properties of astrophysical candidates for accelerating cosmic rays beyond 10^{20} eV (see e.g. Kotera & Olinto 2011). Among the possible candidates, much theoretical attention have been given in particular to AGN (e.g. Ginzburg & Syrovatskii 1964; Hillas 1984; Biermann & Strittmatter 1987; Berezinsky et al. 2006; Berezhko 2008). In fact, the dimension and magnetic field of an AGN jet could in principle accelerate particles to extreme energies (Halzen & Zas 1997); however, it is not easy to develop a model which describes an efficient acceleration mechanism (see Letessier-Selvon & Stanev 2011, and references therein). Although different solutions have been proposed, there are many aspects that need further investigation from both observational and theoretical point of view. As already suggested in Nagano & Watson (2000), we need to revise the parameters (size and magnetic fields) in jets/lobes of AGN, and the strength of the magnetic field in the local region of the Universe. To date, the latter is quite hard to estimate, but the SKA will open a new window in the study of cosmic magnetism, especially regarding the poor-known extragalactic magnetic field (Beck et al. 2007; Beck et al. 2015; Johnston-Hollitt & et al. 2015). Moreover, the SKA will enable a deeper understanding of the properties and energetics of AGN jets and lobes.

This Chapter focus on the advances we can achieve in jet physics with the SKA and is organized as follows: Sect. 2 shows the current state-of-the-art characterization of relativistic jets associated with AGN, comparing observations made at different angular scale with the structure predicted by numerical simulations; Sect. 3 discuss the long-term search for astrophysical sources of ultra high energy cosmic rays (UHECRs), giving particular attention to AGN as candidate sources; Sect. 4 illustrate how the SKA will shed light on this fascinating enigma. Further related topics are discussed in other Chapters of this book, as relativistic jets are amazing laboratories to test both general relativistic (or special relativistic) magnetohydrodynamic and radiation microphysics at work (e.g. Agudo et al. 2015; Gaensler et al. 2015; Giroletti et al. 2015).

2. AGN Jets

The process of accretion powers the most energetic phenomena known in the Universe, such as AGN, their stellar-mass analogues (X-ray binaries), and gamma-ray bursts (GRBs). In all cases, the accretion process is directly coupled to outflows from the systems in the form of powerful, collimated jets (in some cases accelerated close to the speed of light). The presence of relativistic electrons and magnetic fields in jets implies that they emit synchrotron radiation, which is the dominant emission process in the radio regime. The rapid injection of kinetic energy into ambient media universally results in outbursts of synchrotron radiation resulting from the acceleration of particles and compression of magnetic fields. These outbursts are observed from a variety of sources (e.g. van der Laan 1966; Marscher & Gear 1985; Cawthorne & Wardle 1988; Hughes et al. 1989). Detection and monitoring of such outbursts serves several purposes. In fact, it allows us to estimate the feedback of kinetic energy from the central source, to compare this to the available

energy (whether, e.g., from accretion, rearrangement of magnetic fields, etc), in order to understand how this feedback affects the surrounding medium. To date, the studies in the field of AGN relativistic jets benefit on a fertile sinergy between multi-frequency studies in the high-energy (X ray, γ-ray, TeV) domain, and high resolution radio (and sometimes optical) observations. To proper investigate how jets themselves and their host system work, it is crucial to know their energy, mass, velocity, composition, and any possible connection between the power in the jet and the power associated with the release of gravitational energy of mass accreting on the central black hole. However, the estimate of power transported in jets from the observed radiation can be affected by large uncertainties. These mainly include our ignorance on: i) the jet composition (whether the plasma is dominated by a proton-electron component, or electron-positron pairs one); ii) the filling factor, i.e. the fraction of the volume actually permeated by the emitting plasma; iii) the extension of the emitting particle distribution - as this is typically steep, the low energy part is crucial in determining the total number of particles, but self-absorption in the radio band[1] makes it hard to directly observe it. The widely used approach is to compare estimates on different scales, derived by independent data sets, information and modeling and to see if a quantitative consistent picture emerges (e.g. Celotti & Ghisellini 2008).

The combination of multi-frequency monitoring data with regular VLBI observations, as available with e.g. the MOJAVE project (Lister et al. 2009), is essential to understand the nature of the extreme variability and therefore the structure and dynamics of parsec-scale relativistic jets (e.g. Marscher et al. (2010)). There is now growing evidence of a close connection between γ-ray emission and pc-scale radio jet properties of blazars and radio galaxies. However, we are still missing answers (even at least partial) to the following questions: i) what is the role of magnetic fields? More specifically, what is the magnitude of the magnetic fields? what is the configuration of magnetic field in jets? ii) what is the influence of the jet on the surrounding matter? is an AGN jet capable to accelerate particles up to the highest energies?

To date, the acceleration, collimation and stability of the observed jets remain key issues. Theoretical modeling of these jets demands to combine general (or special) relativistic magnetohydrodynamics with radiation microphysics, in order to associate the observed emission features to both the radiation microphysics and macroscopic dynamics. So far, numerical simulations revealed that the highly collimated AGN jets are subject to the Kevin-Helmholts (KH) instability when kinetically dominated, whereas they are disposed to current driven (CD) instability, where the current flows are high and jets are magnetically dominated (e.g. Hardee (2011)). The simulations predict how the structures associated to those instabilities develop and which structures dominate the jet dynamics, thus comparing the observed jet features with theoretically predicted structures can shed light on macroscopic jet properties, and, at the smallest scales, on the conditions in the jet launching region. In fact, at the largest angular scales the jets are kinetically dominated; although they may contain pressure equipartition magnetic fields, strong magnetic fields should exist close to the acceleration and collimation zone, as suggested by several theoretical works (see e.g. Blandford (1976); Blandford & Znajek (1977); Blandford & Payne (1982); Lovelace (1976); Koide et al.

---

[1] At low enough frequencies (e.g. $\sim$ 100 MHz), any synchrotron source will become opaque to radiation. However, compact radio sources (e.g. AGN with size much less than 1 Kpc) with very high synchrotron electron densities start to self-absorb yet at higher frequencies (see Marscher 1987, for details). On the other hand, the relativistic particle densities in the extended radio components are low enough that they can remain optically thin even at very low radio frequencies.

(2000); Nishikawa et al. (2005); De Villiers et al. (2003, 2005); Hawley & Krolik (2006); McKinney & Gammie (2004); McKinney (2006); Mizuno et al. (2007)). At the largest scales, jets are useful as probes of the external environment: large angular structure such as those seen in Virgo A or NCG 1265 imply that jets are less dense than the intra-cluster medium and are carrier of a huge energy flux (De Young 2006).

Radio source morphology starts to show differences at intermediate spatial and angular scales, and those differences give hints on the properties of jets in these objects: namely, the basic two source classes were first classified by Fanaroff & Riley (1974) and are now known as FR-I (whose jets decollimate to form long tails) and FR-II (where jets remain highly collimated to the outer edge of large radio lobes). The morphology is connected to the jet power as on average FR-II jets are more powerful. Furthermore, the morphology can be related to the properties of stability of their jets: in FR-I the jet loses its collimation from interactions with the surrounding environment as the KH instability develops at the interface with the external medium and outer mass is pulled into the jet. Many theoretical works focused on determining the physical conditions which suppress the onset of KH instability in order to keep the jets highly collimated as in FR-II (see Hardee (2011) and references therein for further details). Numerical simulations revealed that organized magnetic fields in pressure equipartition also enable sensible stabilization and reduce mass entrainment (Rosen et al. 1999). However, detailed understanding of the flow properties are still elusive at intermediate scales, even if they can still provide useful constrains on stability requirements.

Finally, at the smallest scales (i.e. tens to hundred of parsecs) the detection of twisted emission structures permits to determine more precisely the jet properties. The analysis of internal jet structure combined with motions allows for identifying macroscopic properties of kinetically dominated jet flows: this technique has been considerably used so far to extract the jet parameters in M87, the most well-studied extragalactic jet (see e.g. Lobanov et al. (2003)). Moreover, the presence of a spine-shear jet morphology is suggested in TeV BL Lacs as they require extreme relativistic bulk motions in the γ-ray emission region while observed proper motion are much slower (Ghisellini et al. 2005). Organized magnetic fields become crucial to explain jet dynamics and structure at those scales, as theoretical and numerical works showed that jets are expected to exhibit (potentially observable) helical structures driven by instability.

This excursus on AGN jets at all angular scales shows how magnetic fields are ubiquitous in these astrophysical objects, and how MHD-formed structures are important to explain the dynamics of the jet itself. A proper knowledge of the magnetic field distribution along the jet is fundamental, also because variations of magnetic fields in space and time imply the existence of transient electric fields, which can possibly accelerate charged particles in the jet to the highest energies (see sect. 3). Thus, understanding magnetic field structure in jets is crucial to put constraints on the UHECRs production models in AGN.

3. The long standing search for sources of UHECRs

How to accelerate cosmic rays up to 10^{20} eV is a pending question since their very first detection in the 1960s. Although the extragalactic nature of UHECRs is widely accepted, their actual origin is still far from being understood (Allard 2012). It is crucial to recognize that the energy in a source capable of accelerating particles to 10^{20} eV and beyond must be extremely large. The

size of the acceleration region R is assumed to be comparable to the Larmor radius of the particle in the magnetic field B, which must in turn be sufficiently weak to avoid that synchrotron losses overcome the energy gain. It can be shown easily that the total magnetic energy in the source scales as the Lorenz factor of the particle to the fifth power; for 10^{20} eV the magnetic field energy must be greater than 10^{57} erg, with $B < 0.1G$. Such sources are likely to be strong radio emitters with radio power exceeding 10^{41} $erg\ s^{-1}$, unless hadrons are being accelerated and electrons are not. This general argument does not specify which acceleration mechanism is invoked. The conditions on potential acceleration sources are summarized in the Hillas plot (Hillas 1984), which relates the maximum energy of a charged particle and the size and strength of the magnetic field of the astrophysical object. A quick look at the Hillas plot shows clearly that only a few astrophysical sources are capable to satisfy this necessary, even if not sufficient, requirement. The list of possible candidates includes neutron stars and other similar compact objects, large-scale shocks due to merging galaxies or clusters of galaxies, the core and the jets of AGN, hot spots of FR-II radio galaxies, and processes associated with GRBs. In particular, AGN have long been investigated as potential origin of such extreme energetic particles (e.g. Biermann et al. 2009; Gizani 2012; Bykov et al. 2012; Tavecchio 2014). Although the properties of core of AGN could in principle lead to accelerate protons to a few tens of EeV, the high radiation field around the central engine is likely to interact with the accelerated protons while energy losses due to synchrotron radiation, Compton processes, and adiabatic losses will take place. Bhattacharjee & Sigl (2000) show that such processes may reduce the maximum energy to only a small fraction of EeV, particularly in the case of nuclei as they will photodisintegrate faster. To overcome this problem, the acceleration must take place in a region with lower radiation density, away from the active center, such as in the terminal shock sites of the jets, a requirement possibly fulfilled by FR-II galaxies, which combine a very powerful engine and relativistic blast waves (with Lorentz factor of the order 2-10) together with a relatively scarce environment (Letessier-Selvon & Stanev 2011). Hence, their hot spots (where the jets terminate) satisfy the acceleration requirement but also the criterion that the accelerated particles does not loose all of the energy gained on the way out of the source (Rachen & Biermann 1993; Hardcastle 2010). In particular, Hardcastle (2010) details how stocastic acceleration in the large-scale lobes of radio galaxies is viable to produce UHECRs, but acceleration to the highest energies put strong constrains on the properties of the cosmic sources, indicating only a small number of local radio galaxies as plausible candidates (if UHECRs are protons).

Although the diffusive shock acceleration (Malkov & O'C Drury 2001), based on the Fermi process, is the most invoked mechanism, several alternative models have been proposed. This list comprises: unipolar inductors (Berezinskii et al. 1990; McKinney et al. 2012), magnetic reconnection acceleration (Zweibel & Yamada 2009; Giannios 2010), wakefield acceleration (often related to ponderomotive acceleration; Tajima & Dawson (1979)), re-acceleration in sheared jets (Lyutikov & Ouyed 2007), and "magnetoluminescence"(Blandford et al. 2014). None of this model is free of open issues, especially regarding their efficiency. For example, Pelletier et al. (2009) state that the Fermi 1st order mechanism is not so efficient around ultra-relativistic shocks, unless amplification is provided by effects outside the MHD range (Pelletier et al. 2009) or shear acceleration (Lyutikov & Ouyed 2007). Recently, Giannios (2013) shows how reconnection-driven plasmoids in blazars can effectively dissipate magnetic energy in the flow and power blazar emission, if the magnetic field is appropriate. On the other hand, Blandford et al. (2014) point out that the rela-

tivistic magnetic reconnection is unfortunately an unproved possibility of acceleration, even if it remains an attractive one. Ebisuzaki & Tajima (2014) show instead that wakefield acceleration mechanism arising from the Alfvénic pulse incurred by an accretion disk around the central supermassive black hole could be a viable way to accelerate particle well beyond 10^{20} eV. Moreover, the production rate of UHECRs in this model is found to be consistent with the observed γ-ray luminosity function of blazars and makes predictions on their time variability.

In this pletora of models, it is clear that several aspects demand dedicated studies. In particular, we need to revise both the parameters (size and magnetic fields) in jet/lobes of AGN, and the strength of the magnetic field in the local supercluster, as several models still rely on quite generous hypotesis on the value of these parameters. Moreover, it is worth noting that to-date there is no robust or direct measurement of the magnetic field in the jets and lobes of FRI sources, which constitute the numerically dominant population of radio galaxies in the local universe.

The SKA promises to move a huge step forward in the study of cosmic magnetism and will be able to address these issues. In particular, the SKA and its pathfinders will allow for a better characterization of: i) the magnetic field strength and its structure within the jet of an AGN; ii) the overall jet properties and energetics. These efforts will improve our knowledge in this class of cosmic accelerators, in particular regarding how they contribute to the observable flux of UHECRs.

4. Relativistic Jets in the SKA era

The SKA will dramatically improve our understanding of AGN jet with respect to both structure and dynamics: in fact, it will permit not only to image the full extent of the radio emission coming from the jet, but also to characterize polarization and to track the evolution of emission features within the jet (Bicknell et al. 2004). The unprecedented sensitivity and VLBI-scale angular resolution will allow the SKA to study in details the parameters of the nearby γ-ray AGN, which are to date the best candidate sources of UHECRs.

4.1 SKA1

Due to its relative proximity (d $\sim$ 16 Mpc), the jet of M87 has been used so far as a suitable laboratory to constrain jet structure and dynamics. The SKA will permit to extent these kind of studies to a larger sample of objects, since the SKA1 early science phase (see 4.1.1). In fact, SKA1-MID can detect features similar to the HST-1 seen in M87 jet up to 100 Mpc, with observing time of few minutes (Wolter et al. 2013). The resolution needed is of the order of 0.1 arcsec that will be achieved with the largest SKA1 planned baseline. This more detailed census of the properties of "local" AGN jets is fundamental as the effect of interactions between extragalactic cosmic rays and the cosmic background radiation causes the Greisen-Zatsepin-Kuzmin (GZK) cutoff in UHE-CRs spectrum (Greisen 1966; Zatsepin & Kuz'min 1966), implying that the observable sources of UHECRs lie within 100 Mpc (if UHECRs are mainly protons). Therefore, we can simply interpret the results from the Pierre Auger Observatory (i.e. correlations between UHECRs above 55 EeV and the distribution of nearby AGN, Abraham et al. (2007)) as protons from nearby sources within the so-called GZK sphere. Thus, SKA capabilities, especially resolution and sensitivity, will shed light on this topic, with the detailed characterization of all the AGN jets within the GZK horizon in

the southern sky. All these findings will be essential to develop more refined models for the origin and the acceleration of UHECRs, constraining their flux produced at AGN sites.

The simultaneous multifrequency capabilities offered by SKA1 will be crucial to investigate deeply different jet parameters. For Phase 1 specification, SKA1-MID observations in Band 1, Band 4, Band 5 (350-1050 MHz, 1.65-3.05 GHz, and 4.6-13.8 GHz) will characterize the source spectrum from the MHz to the GHz. Using all the baselines available, the observations will determine the angular size of features in the jets. At lower frequencies and hence lower energies the electrons start to self absorb the emitted photons and the spectral index changes accordingly. Once the size of a source and its spectrum are known, it is straightforward to calculate the strength of the magnetic field (Marscher 1983). For *Chandra*-detected jets, other useful constraints on the magnetic field will come from the interaction of the jet emission with the CMB (see Jorstad & Marscher 2004). Moreover, the comparison of MHz and GHz studies of energy budget (via SED[2] modeling) can tell us if it implies the existence of a strong magnetic field gradient. This will permit also to get information on the minimum electron energy, which is currently one of the less constrained parameter in the analysis of jets.

Besides the magnetic fields, the data will provide contraints on the bulk and particle Lorentz factors, the Doppler factor, and the jet viewing angle. These parameters will also improve our knowledge on the poorly-constrained low energy end of the particle energy spectrum.

Furthermore, the measurement of linear polarization allows for mapping the magnetic field direction in extended jets, such as those of FRI radio galaxies. Then, the polarization capabilities offered by SKA1 will give us a more defined and precise description of the magnetic fields role in jets. The comparison between the measured percentages of linear and circular polarization will then put constrains on different models: for example, a conversion of part of linear to circular polarization is expected in optically thick regions.

SKA1-LOW and SKA1-SUR observations can add data to built complete radio spectra and SEDs for the sources, even if their capabilities will not allow for the detection for HST-1-like feature up to 100 Mpc. In particular, we could better characterize the source spectrum if SKA1-SUR data cover a Band not available at this stage with SKA1-MID.

Among the greatest capabilities offered by the SKA there is the chance of doing repeated observations, as these will make feasible to address several key issues in jet physics: in fact, individual snapshots of SEDs can probe only a partial picture of the underlying physical mechanisms. In fact, a common feature of many jet models is that emission at different frequencies comes from different regions in the jet. This implies that the instantaneous SED measured in the observer's reference frame plausibly originates from spatially separated zones. If we fit an individual SED in terms of a single population of energetic particles, we are not considering that the energy distribution may evolve as particles are moving through the jet. Indeed, if the particle energy distribution does vary temporally, and thus spatially, it may be impraticable to really reproduce each individual instantaneous SED with a single particle distribution. Time dependent modeling becomes therefore clearly essential for understanding jet physics. This necessarily increases the complexity of the modeling, and demands for extensive computing resources. However, theorists are currently at work to incorporate time-dependence in jet modeling (e.g. Maitra et al. (2009)). Moreover, jet monitoring

---

[2]Spectral Energy Distribution

will allow us also to test theoretical predictions on variability structures. It is worth to point out here that on-going efforts in improving simulations will sensibly reduce the risks of being stuck by immature and weak models when we will be plenty of data in the SKA era.

4.1.1 Early science with SKA1

To address this topic, we consider as early science the SKA1 phase when only the 50% of the full SKA1 capabilities will be deployed. For example, if only half of the maximum programmed baseline is available during early science, this will prevent detection of an HST-1-like feature up to 100 Mpc with the SKA1-MID, and of course it will lower the possible detections even more if considering SKA1-SUR and SKA1-LOW observations. Thus, in this phase only the closest sources will be studied, postponing the complete census of the local AGN when the full maximum baseline will become available. On the other hand, a cut in sensitivity of 50% will imply simply the need for longer observations to detect HST-1-like features up to 100 Mpc (providing that we have only a reduction of sensitivity but we retain the maximum baseline). In the least favourable case, i.e. a simultaneous cut of 50% in both sensitivity and maximum available baseline, we can focus on the closest and brightest source, to test for example different observational strategies (to determine e.g. the optimal cadence for repeated observations), and to obtain a set of observations that will serve as a proof of principle of what will be done when the array will reach it full capabilities.

However, it would be desirable to have available even at these early stages at least Band 1 and Band 5 for the SKA1-MID: in fact, Band 1 will allow us to get MHz fluxes for the sources, where their spectrum is expected to be more self-absorbed, whereas Band 5 will be less contaminated by steep spectrum sources and suffer of lower depolarization effects. Moreover, Band 1 probes older electrons in the external part of the jet, since MHz frequencies sample kpc spatial scales. This allows us to study extended emission at large distances from the compact object driving the jets and possibily obtain hints on the interaction between the jet and circumnuclear regions, or jet-feedback, thus helping us to determine the impact of the jets on their surroundings. Combining observations made at different wavelengths will trace the structure of the jets.

4.2 SKA Phase 2

The SKA superb improvement in sensitivity will make possible to monitor "local" AGN with really short snapshots with an unprecedented angular resolutions. Moreover, the extention up to 30 GHz of Band 5 is important as the highest frequencies probe closer to the AGN radio core, that is detected so far at 43 GHz. Moreover, the longest baseline available with the SKA-MID highest band (and possibly an integration with other arrays providing longer baselines) will allow us to observe the nearby AGN at smaller angular scale and measure: (i) structures such as helical twists or shock transitions, (ii) proper motions, (iii) polarization and so characterize the magnetic geometry within the jet, (iv) the spectral and temporal evolution of the emission. All of them are required to understand both the dynamics and the microphysics of AGN jets (Hardee 2008). Polarization data will trace changes in the magnetic geometry that will allow us to better identify transition points. If longer baselines will be available, thanks to the integration of SKA with the African VLBI, in the case of exemplary obiects such as M87, new observations will locate beyond any doubt the base of the kinetically dominated region, and this will permit to set robust constrains on jet formation models using the spatial distance from the origin and the rate of collimation out to

this point. Moreover, the eventual detection of deceleration or acceleration in proper motions along the jet at these spatial and angular scales will have impact on high energy emission models, notably in the TeV band. Among other importante observables, transverse emission structures will play a key role in reconstructing the jet spine-sheath structure, when combinated with proper motion measures. This will give us an unique view of the jet of M87.

Furthermore, as stated earlier, the SKA will permit for the first time to extent the present studies on individual sources as M87 to a more statistically significant sample of objects, also covering a wider range in redshift and evolution. This unprecedented data set will be fundamental in hunting answers for the following open questions: has M87 just a peculiar jet of its own or is it the perfect prototype for jets in radio galaxies? More generally, what kind of jets the nature makes? Is there simply a dichotomy as the radio galaxy morphology points out? Which are the parameters that preserve jet stability? More specifically, is it more a matter of galaxy/enviroment in which the AGN lie or is it related mainly to jet power? Is there any evolution in the jet key parameters in the local Universe? Which jets can accelerate particles to extreme energies?

However, a complete jet picture can be achieved only integrating SKA obervations with VLBI-(sub)mm information, and this implies to plan synergies between SKA and ALMA. Moreover, synergies with the Cherenkov Telescope Array (CTA) will allow us to perform radio/VHE correlation studies with greatly improved VHE sensitivity, thus giving major contributions in particle acceleration in nearby γ-ray AGN, improving our knowledge of the jet-structure and jet-composition at different locations from the main engine. All these studies inform ongoing efforts to improve our understanding of the particle acceleration mechanisms in AGN jets, and possibly solving the long-standing enigma of the origin of ultra-energetic particles.

References

Abraham, J., Abreu, P., Aglietta, M., et al. 2007, Science, 318, 938

Agudo, I., Boettcher, M., Falcke, H., et al. 2015, "Studies of Relativistic Jets in Active Galactic Nuclei with SKA", in proceedings of "Advancing Astrophysics with the Square Kilometre Array", PoS(AASKA14)093

Allard, D. 2012, Astroparticle Physics, 39, 33

Beck, R., Bomans, D., Colafrancesco, S., & et al. 2015, "Structure, dynamical impact and origin of magnetic fields in nearby galaxies in the SKA era", in proceedings of "Advancing Astrophysics with the Square Kilometre Array", PoS(AASKA14)094

Beck, R., Gaensler, B., & Feretti, L. 2007, in Exploring the Cosmic Frontier: Astrophysical Instruments for the 21st Century, ed. A. P. Lobanov, J. A. Zensus, C. Cesarsky, & P. J. Diamond (Springer-Verlag), 103

Berezhko, E. G. 2008, ApJ, 684, L69

Berezinskii, V. S., Bulanov, S. V., Dogiel, V. A., & Ptuskin, V. S. 1990, Astrophysics of cosmic rays

Berezinsky, V., Gazizov, A., & Grigorieva, S. 2006, Phys. Rev. D, 74, 043005

Bhattacharjee, P., & Sigl, G. 2000, Phys. Rep., 327, 109

Bicknell, G. V., Jones, D. L., & Lister, M. 2004, New A Rev., 48, 1151

Biermann, P. L., & Strittmatter, P. A. 1987, ApJ, 322, 643

Biermann, P. L., Becker, J. K., Caramete, L., et al. 2009, Nuclear Physics B Proceedings Supplements, 190, 61

Blandford, R., Simeon, P., & Yuan, Y. 2014, arXiv:1409.2589, "Cosmic Ray Origins: An Introduction", in Proceedings of the "Cosmic Ray Origin - Beyond the Standard Models" International Conference, Nuclear Physics B Proceedings Supplement. Eds. O. Tibolla, L. Drury, M. Persic, S. Kaufmann, H. Völk, K. Mannheim and A. de Angelis

Blandford, R. D. 1976, MNRAS, 176, 465

Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883

Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433

Bykov, A., Gehrels, N., Krawczynski, H., et al. 2012, Space Sci. Rev., 173, 309

Cawthorne, T. V., & Wardle, J. F. C. 1988, ApJ, 332, 696

Celotti, A., & Ghisellini, G. 2008, MNRAS, 385, 283

De Villiers, J.-P., Hawley, J. F., & Krolik, J. H. 2003, ApJ, 599, 1238

De Villiers, J.-P., Hawley, J. F., Krolik, J. H., & Hirose, S. 2005, ApJ, 620, 878

De Young, D. S. 2006, ApJ, 648, 200

Ebisuzaki, T., & Tajima, T. 2014, Astroparticle Physics, 56, 9

Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31P

Gaensler, B., Agudo, I., Akahori, T., et al. 2015, "Broadband Polarimetry with the Square Kilometre Array: A Unique Astrophysical Probe", in proceedings of "Advancing Astrophysics with the Square Kilometre Array", PoS(AASKA14)103

Ghisellini, G., Tavecchio, F., & Chiaberge, M. 2005, A&A, 432, 401

Giannios, D. 2010, MNRAS, 408, L46

—. 2013, MNRAS, 431, 355

Ginzburg, V. L., & Syrovatskii, S. I. 1964, The Origin of Cosmic Rays (Macmillan, New York)

Giroletti, M., Orienti, M., D'Ammando, F., et al. 2015, "The connection between radio and high energy emission in black hole powered systems in the SKA era", in proceedings of "Advancing Astrophysics with the Square Kilometre Array", PoS(AASKA14)153

Gizani, N. A. B. 2012, Nuclear Instruments and Methods in Physics Research A, 692, 280

Greisen, K. 1966, Physical Review Letters, 16, 748

Halzen, F., & Zas, E. 1997, ApJ, 488, 669

Hardcastle, M. J. 2010, MNRAS, 405, 2810

Hardee, P. 2008, Journal of Physics Conference Series, 131, 012052

Hardee, P. E. 2011, in IAU Symposium, Vol. 275, IAU Symposium, ed. G. E. Romero, R. A. Sunyaev, & T. Belloni, 41–49

Hawley, J. F., & Krolik, J. H. 2006, ApJ, 641, 103

Hillas, A. M. 1984, ARA&A, 22, 425

Hughes, P. A., Aller, H. D., & Aller, M. F. 1989, ApJ, 341, 54

Johnston-Hollitt, M., & et al. 2015, "Using SKA Rotation Measures to Reveal the Mysteries of the Magnetised Universe" in proceedings of "Advancing Astrophysics with the Square Kilometre Array", PoS(AASKA14)092

Jorstad, S. G., & Marscher, A. P. 2004, ApJ, 614, 615

Koide, S., Meier, D. L., Shibata, K., & Kudoh, T. 2000, ApJ, 536, 668

Kotera, K., & Olinto, A. V. 2011, ARA&A, 49, 119

Letessier-Selvon, A., & Stanev, T. 2011, Reviews of Modern Physics, 83, 907

Lister, M. L., Cohen, M. H., Homan, D. C., et al. 2009, AJ, 138, 1874

Lobanov, A., Hardee, P., & Eilek, J. 2003, New A Rev., 47, 629

Lovelace, R. V. E. 1976, Nature, 262, 649

Lyutikov, M., & Ouyed, R. 2007, Astroparticle Physics, 27, 473

Maitra, D., Markoff, S., & Falcke, H. 2009, A&A, 508, L13

Malkov, M. A., & O'C Drury, L. 2001, Reports on Progress in Physics, 64, 429

Marscher, A. P. 1983, ApJ, 264, 296

Marscher, A. P. 1987, in Superluminal Radio Sources, ed. J. A. Zensus & T. J. Pearson, 280–300

Marscher, A. P., & Gear, W. K. 1985, ApJ, 298, 114

Marscher, A. P., Jorstad, S. G., Larionov, V. M., et al. 2010, ApJ, 710, L126

McKinney, J. C. 2006, MNRAS, 368, 1561

McKinney, J. C., & Gammie, C. F. 2004, ApJ, 611, 977

McKinney, J. C., Tchekhovskoy, A., & Blandford, R. D. 2012, MNRAS, 423, 3083

Mizuno, Y., Hardee, P., & Nishikawa, K.-I. 2007, ApJ, 662, 835

Nagano, M., & Watson, A. A. 2000, Reviews of Modern Physics, 72, 689

Nishikawa, K.-I., Richardson, G., Koide, S., et al. 2005, ApJ, 625, 60

Pelletier, G., Lemoine, M., & Marcowith, A. 2009, MNRAS, 393, 587

Rachen, J. P., & Biermann, P. L. 1993, A&A, 272, 161

Rosen, A., Hardee, P. E., Clarke, D. A., & Johnson, A. 1999, ApJ, 510, 136

Tajima, T., & Dawson, J. M. 1979, Physical Review Letters, 43, 267

Tavecchio, F. 2014, MNRAS, 438, 3255

van der Laan, H. 1966, Nature, 211, 1131

Wolter, A., Tavecchio, F., Bonnoli, G., et al. 2013, "Relativistic Jets with SKA" in "Italian SKA White Book", INAF Press

Zatsepin, G. T., & Kuz'min, V. A. 1966, Soviet Journal of Experimental and Theoretical Physics Letters, 4, 78

Zweibel, E. G., & Yamada, M. 2009, ARA&A, 47, 291