Relativistic Jets

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Despite substantial observational and theoretical progress over many years, numerous key questions surrounding the topic of relativistic jets remain to be answered. In particular we still do not know how they are ejected from the supermassive black holes that are implicated in their production and we do not know how the ejection of matter at relativistic speeds is related to the properties of the parent galaxy. We are also just beginning to appreciate the role that relativistic jets play in the feedback loop between black holes and forming galaxies. The SKA will have a major impact in this field. The ability to image low luminosity sources and to map out the details of the interaction between jets and their environments will assist in understanding much of the physics of relativistic jets that is currently inaccessible.

1. Introduction

The physics of relativistic jets has dominated the subject of extragalactic radio sources ever since the discovery of superluminal motions in quasars and the interpretation in terms of a relativistic expanding flow (Rees 1966). The subject has developed both observationally and theoretically ever since and its current observational status is possibly best represented in the paper by Kellerman et al. (2004) which analyzes the culmination of detailed observations of 110 active galaxies with the VLBA. Nevertheless, despite the progress that has been made, we still do not understand some of the key questions relating to extragalactic jets: What are their initial velocities? How are they ejected from the environs of a black hole? What is the relationship between jet power and galaxy type? As well as these key questions, we are just starting to realise the importance of jets in their interaction with the environment and their possible role in the symbiosis between black holes and galaxy formation. In the following sections, we outline how observations with the SKA will be used to address some of the key physics associated with relativistic jets.

2. Imaging of jets and related structure in powerful radio sources

2.1. Structure of parsec-scale jets

For the most part, current radio images of jets on the scale of a few parsecs, show a succession of bright knots moving with a range of apparent speeds, ranging from subluminal to highly superluminal and without a clear relationship emerging between the speed of the knots and that of the underlying flow (Kellermann et al. 2004) . A detailed analysis of high dynamic range observations of 3C273 (**?**), reveals a complex structure that has been interpreted in terms of growing surface and body modes of the Kelvin–Helmholtz instability. Higher sensitivity observations will enable the structure of many more jets to be analyzed in this way, to trace their structures to hundreds of milliarcseconds from the core, to ascertain the viability of jet instability models for the production of knots and to consider other models discussed below.

Appealing models for the launching of relativistic jets (Blandford & Payne 1982; Blandford & Znajek 1977) invoke magnetic fields to drive the plasma away from the black hole resulting in a jet whose power is dominated by electromagnetic fields - a Poynting flux dominated jet. Simulations of such jets explain observed helical structures in terms of magnetic kink instabilities (Nakamura, Uchida, & Hirose 2001) providing an alternative to the Kelvin-Helmholtz instability model. The sensitivity and dynamic range of the SKA used to image such jets over several tens of parsecs should be able to detect the predicted magnetic structures. On the other hand, current radio observations and recent gamma-ray observations indicate that jets are particle dominated (Konopelko et al. 2003) raising the question as to whether magnetic field is destroyed (by reconnection) on the smaller scales. Signatures of reconnection occurring on scales imaged by the SKA would include local particle acceleration and complex magnetic field structures.

2.2. Information from counter–jets.

Parsec-scale radio counter–jets are important for studying the intrinsic symmetry of the jet-formation process, and as probes of the structure of ionized gas in the central pc of accretion disks surrounding the central black holes in AGN. The phenomenon of relativistic beaming reduces the observed flux from counter-jets. However, the modest number of counter–jets that have been detected so far in extragalactic sources have revealed the effects of free–free absorption of the counter–jet by thermal electrons in the accretion disk around the black hole (Walker, Romney, & Benson 1994; Walker et al. 2000; Tingay & Murphy 2001). The counterjet serves as a source of radiation which is absorbed by thermal electrons in the disk. If geometrically thin, the disk covers the inner part of the counterjet but not the approaching jet. If geometrically thick, the core and perhaps the base of the approaching jet may also be absorbed, but with lower total optical depth than the base of the counterjet. Multi-frequency observations can detect the highly inverted spectrum created by free-free absorption from flat or steep spectrumcsynchrotron emission from the radio core and jet. Even in cases where the radio core has an inverted spectrum because of synchrotron self-absorption, it is possible to use the differing angular size of free-free absorbing regions as a function of frequency to distinguish this process from synchrotron self-absorption.

The high sensitivity of the SKA and its low frequency capability will enable the study of many counter–jets that have hitherto been too faint. Thus, SKA observations of free-free absorption in jet sources will enable the ionized medium close to the black hole to be probed in a much larger number of active galaxies.

2.3. Doppler factors in variable sources

A fraction ($\sim$ 15%) of extragalactic radio sources exhibit rapid variability that, interpreted naively, implies very high brightness temperatures (see contribution by Lazio et al., this volume). It is now widely accepted that many rapidly variable sources can be interpreted in terms of scintillation in the interstellar medium of our Galaxy. However, there is now good evidence that one variable source, J1819+3845, has a high intrinsic brightness temperature $\sim 10^{14}$°K, implying a Doppler factor ~ 100 in the emitting region (Macquart & DeBruyn 2004), even though scintillation is implicated as part of the reason for the rapidly varying flux density. Until recently, there has been little direct evidence for such high Doppler factors. However, rapid variability in the TeV blazars MKN 421 and MKN 501 provides strong evidence for Doppler factors ≈ 50. In another unexpected result, analysis of restarting jets in the radio galaxy, PKS 1545-321, indicates a Lorentz factor ≈ 20 (Safouris et al. 2004). Thus once again we have to consider the possibility of intrinsic high brightness temperatures and Doppler factors in extragalactic radio sources and the implications for the way in which jets are accelerated. The SKA will be a high sensitivity ground element in space–VLBI observations which will be an effective probe of extreme brightness temperatures and which may even be able to determine the geometry of the emitting region in the core. The high sensitivity of the SKA as a space–VLBI element, extends the number of sources that can be investigated in this way. The high sensitivity also reduces the required bandwidth, minimizing the effects of interference and also making possible detailed VLBI monitoring studies (in conjunction with multi–beaming).

The connection between radio emission and high energy emission (from X–rays through to γ–rays) is also one that can be effectively explored by the SKA. Non–thermal X–ray and γ–ray emission probes conditions within 100–1000 gravitational radii of the black hole – a critical region where, according to some theories, the jet flow is being established. The component of the radio emission emitted on these scales is self absorbed and is predicted to be faint. However, the sensitivity of the SKA should enable the detection of such a component as it moves out through the jet. This would give us information on the electron/positron population in this spatial region over a very wide range in particle energy and the way which emitting, shocked or reconnecting regions move out through the jet.

2.4. Low surface brightness emission associated with young and evolved radio sources.

Radio galaxies are generally believed to have been born following major or minor mergers with companion galaxies. In many radio galaxies and quasars, we observe an unobstructed pair of jets and the study of such jets has formed much of the basis of extragalactic radio astronomy, to date. However, in the early stages ($\sim 10^6$ yrs) of radio galaxies, the jets appear to interact with merger debris in the vicinity of the nucleus, and are substantially disrupted. A well–known example is the quasar 3C 48 (Wilkinson et al. 1991) but there are numerous other examples amongst the class of sources known as Gigahertz Peak Spectrum (GPS) and Compact Steep Spectrum (CSS) sources. Simulations of jets passing through a clumpy medium show that not only is the disrupted jet evident, but in addition, large–scale structure is predicted that is mostly in the form of an energy driven bubble of radio–emitting plasma (Bicknell et al. 2003). Sensitive observations of 3C 48 (which is classified as a CSS quasar) and MKN 501 (a TeV γ–ray blazar) (Giroletti et al. 2004) indeed reveal such structure. The effects of propagation through a clumpy medium is also evident on larger scales in sources such as M87 (Owen, Eilek, & Kassim 2000) which shows a hierarchical structure that may be associated with jet propagation through an inhomogeneous medium. Other radio sources, such as 3C84 in the Perseus A cooling flow, show evidence for earlier outbursts of radio–emitting plasma, that have probably interacted with and possibly heated the cooling flow (Fabian et al. 2002). In all such cases, sensitive, well–resolved low frequency observations can reveal the existence of earlier activity and delineate more clearly, the early stages of radio galaxies. With the SKA, we will be able to study many more examples of such sources and understand better the relationship between radio sources and their environments. In many of these sources, the wavelength dependence of polarization, observed over a wide range in wavelength, will illuminate the (probably fractal–like) structure of the interstellar medium.

All of these interactions are indicative of a close relationship between relativistic jets and various stages of galaxy evolution. The relationship between black hole and bulge mass (Magorrian et al. 1998; Tremaine et al. 2002) has been taken to indicate feedback between the outflows from black holes and the haloes of forming galaxies (Silk & Rees 1998). Given that inhomogeneity in the interstellar medium can isotropize the jet power, the role of relativistic jets in galaxy formation is probably a fundamental one. We see examples of this feedback at work in high redshift radio galaxies (Chambers et al. 1996), wherein, in many cases, the jets are interacting with the Lyman-α haloes detected in these objects (Bicknell et al. 2000). This raises the interesting prospect that the baryon mass fraction, in at least massive galaxies, is determined by the driving out of baryonic material from forming galaxies (Silk, private communication). As indicated above, the SKA stands to make an outstanding contribution in this area by virtue of its ability, through its sensitivity and low frequency imaging, to map out the details of interactions between jets and forming galaxies.

3. Jets in "Radio-quiet" galaxies, including Seyfert galaxies

The SKA is an ideal tool for studying the physics of low-luminosity AGN, including distant FR1 radio galaxies, so–called radio quiet galaxies, Seyfert galaxies and LINERS. Radio quiet galaxies when observed for a sufficiently long integration time with the VLA often reveal evidence for relativistic jets. For example, the optically bright quasar E1821+643 is host to a 300 kpc long FR1 type jet (Blundell & Rawlings 2001); the "radio-quiet"' but optically luminous quasar PG 1407+263 contains relativistic jets (Blundell 2003). As Blundell has correctly argued the relationship between jets and the various forms of active galaxies has been underexplored (Blundell, Beasley, & Bicknell 2003), the obvious cause being the faintness of low–powered jet sources as we go out in redshift. Both the sensitivity and low frequency capability of the SKA will redress this deficiency in our understanding of the jet phenomenon in relation to *all* types of active galaxy.

These considerations also apply to Seyfert galaxies, which dominate the AGN population in terms of space density, and which typically have radio luminosities $\sim 10^8$ times weaker than the most powerful radio galaxies, even though they harbour highly compact radio sources and supermassive black holes (Nagar et al. 2002). The jets in Seyfert galaxies are no less interesting than those in the more powerful radio galaxies. For example, the Seyfert galaxy III Zw 2 is host to a superluminal, relativistic jet (Brunthaler et al. 2000) which clearly, in velocity, bears the imprint of the relativistic potential from which it was launched. Nevertheless, the reasons for the low radio power of Seyfert galaxies are still not understood. Models involving advection-dominated accretion flows have been found to be insufficient in producing the required radio luminosity, and it now appears likely that a compact jetted outflow is present (Falcke, Körding, & Markoff 2004). Direct imaging of these jets is necessary to obtain a complete picture of the nature of the jet phenomenon, and the phenomenon of radio emission in AGN in general.

Measuring the radio properties of Seyfert cores would greatly improve our knowledge of supermassive black hole demographics, and allow for detailed observational tests of accretion disk/jet models. In particular, measurements of parsec-scale jet speeds from high-sensitivy global VLBI images can place strong constraints on conditions near the jet nozzle (Middelberg et al. 2004), and also aid in determining whether Seyfert jets are dominated by thermal plasma, as opposed to non-thermal plasma in the case of higher power radio galaxy jets (Bicknell et al. 1998). It is presently difficult to obtain such data on suitably-sized samples of Seyferts, because of their radio luminosity and the time-consuming nature of phase-referencing observations.

The linear and circular polarization characteristics of low-luminosity AGN are also important diagnostics of jets and their external environments (Bower, Falcke, & Mellon 2002). However, only a handful of low-luminosity AGN have so far been detected in circular polarization. Seyfert radio sources are generally highly depolarised, so that high sensitivity is essential for examining the Faraday rotation and depolarising effects of the ISM and to sort this out from possible internal depolarisation.

The features of the SKA that will be utilized in all of these observations of radio-quiet galaxies include high angular resolution ans sensitivity and good polarization characteristics.

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