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MASSIVE BLACK HOLE EVOLUTION IN RADIO-LOUD ACTIVE GALACTIC NUCLEI

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ABSTRACT

Active galactic nuclei (AGNs) are distant, powerful sources of radiation over the entire electromagnetic spectrum, from radio waves to gamma-rays. There is much evidence that they are driven by gravitational accretion of stars, dust, and gas, onto central massive black holes (MBHs) imprisoning anywhere from ~1 to ~10,000 million solar masses; such objects may naturally form in the centers of galaxies during their normal dynamical evolution. A small fraction of AGNs, of the radio-loud type (RLAGNs), are somehow able to generate powerful synchrotron-emitting structures (cores, jets, lobes) with sizes ranging from pc to Mpc. A brief summary of AGN observations and theories is given, with an emphasis on RLAGNs. Preliminary results from the imaging of 10000 extragalactic radio sources observed in the MITVLA snapshot survey, and from a new analytic theory of the time-variable power output from Kerr black hole magnetospheres, are presented.

To better understand the complex physical processes within the central engines of AGNs, it is important to confront the observations with theories, from the viewpoint of analyzing the time-variable behaviours of AGNs - which have been recorded over both 'short' human ($10^0 - 10^9$ s) and 'long' cosmic ($10^{13} - 10^{17}$ s) timescales. Some key ingredients of a basic mathematical formalism are outlined, which may help in building detailed Monte-Carlo models of evolving AGN populations; such numerical calculations should be potentially important tools for useful interpretation of the large amounts of statistical data now publicly available for both AGNs and RLAGNs.

Key words : black hole physics — galaxies: active — galaxies: evolution — galaxies: jets — MHD — radio continuum: galaxies

I. INTRODUCTION

There is now much observational evidence for astrophysical black holes (BHs) (Chakrabarti 1999), both stellar and supermassive. Massive black holes (MBHs) are now believed to develop naturally in galactic centers during their normal dynamical evolution (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Kormendy 2001; McLure & Dunlop 2003). We should then expect to find MBH engines in the centers of active galactic nuclei (AGNs), and, in particular, radio-loud AGNs (RLAGNs). Over the past ~40 years, abundant data of various types, and from many independent surveys, have been collected on many thousands of bright, extragalactic radio sources (EGRS); almost all of which are RLAGNs. In the near future, high-resolution imaging data, broad-band spectra, identifications, and redshifts, will become publicly available for these many thousands of RLAGNs. All of this information needs to be correlated, and compared with numerical models based on physical theories for the time evolution of MBHs and their derivative jets, disks, and lobes. RLAGNs form a very large sub-family of AGNs, and their intrinsic luminosities and proper sizes span very broad ranges. Their number density as a function of flux density strongly indicates that they evolve on cosmological timescales, but the details of this long-term evolution are still not fully understood. To compile basic parameters (e.g. luminosities and projected sizes) for a statistically large sample, redshifts need to be secured. This is a difficult task, as the optical counterparts of RLAGNs are usually faint.

The magnetospheric physics of MBHs, and the relativistic plasma, gas, radiation and particle dynamics involved in RLAGN evolution, are all very complex, and so theories have advanced much slower than observations. It is only recently that computer simulations have attacked the general-relativistic MHD (GRMHD) problem of an accreting Kerr BH, which is very difficult even in the axisymmetric (2.5D) case. However, a convergence of theory and observation, for the case of evolving MBHs within RLAGNs, is foreseen for the future.

II. CURRENT STATUS

Based on Einstein's general theory of relativity, we expect that astrophysical BHs should exist; they are almost certainly formed as a result of normal evolutionary processes in stars, as well as from stellar dynam-

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ical evolution within sufficiently dense systems, such as the centers of galactic bulges. There is clear observational evidence (extreme luminosities; broad, nonthermal spectra; optical, radio and X-ray spectral signatures indicating orbital motion around a massive central object) for massive dark objects (MDOs) in the centers of nearby galaxies, and these are very likely to be MBHs. AGNs & RLAGNs are thus expected to develop MDOs during their evolution; during the AGNs' 'luminous' phase, these MDOs should actually be MBHs. In the case of radio-loud AGNs, there is further evidence for MBHs (persistent, large-scale jets with constant spatial orientation and superluminal cores; huge energy stores in extended lobes; strong, linearly polarized synchrotron radiation; radio variability from days to years). Based on all these observational 'smoking guns', we are led to suspect that all RLAGNs harbor not only a MDO, but indeed a MBH.

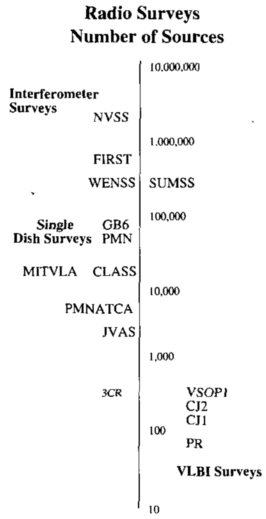

Fig. 1.— Numbers of sources found in large radio surveys (on a logarithmic scale).

Where can we find the RLAGNs which house these putative MBHs? This is where large-area, statistical, surveys of RLAGNs come into play. These surveys come in 4 basic types, and the basic parameters of some of the more important ones are given in Table 1. Depending on the instrument, technique and selection criteria used, the resulting sample sizes range from ~50 to 2 million detected radio sources. Almost all of the surveys listed here are publicly available, with the exception of the interferometer array imaging surveys. Some of these latter large campaign results should become publicly available within the next few years or so.

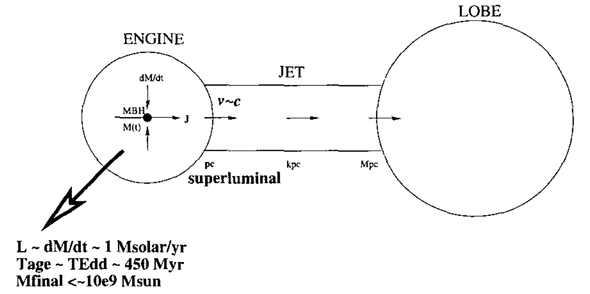

Fig. 2.— Schematic picture of the basic physics in a radio-loud AGN.

A potentially powerful key to investigating RLAGN astrophysics is the confrontation of these abundant survey statistics with global models of cosmologically evolving populations of powerful EGRS. On the hypothesis that each one of these AGNs in fact houses an evolving MBH engine that is the ultimate power source for the distinctive phenomena observed, we may ask the basic question: can we understand all the RLAGN phenomena in terms of models for physically evolving MBHs? The physics of the MBH, of its plasma magnetosphere, and of its attendant accretion disk, will all be crucial links connecting the growth and evolution of the MBH to the observed consequences (jets, lobes, radio spectra) that it drives. Despite the serious lack of redshift information for RLAGNs, what is clear so far is that RLAGNs are usually found in massive elliptical galaxies (e.g. cD, gE) in the centers of galaxy clusters, and that they undergo strong cosmological evolution (Condon 1989). In the high redshift range around $1<z<5$, there was an 'AGN Era' where all AGNs were more luminous (luminosity evolution) or more numerous (density evolution), or a mixture of both. As a corollary, we expect to find non-luminous 'dead quasar' remnants of former AGNs in the centers of nearby galaxies. There also seems to be a peak in the space density of quasars around $2<z<4$ (Shaver et al. 1996), and a redshift cutoff in the space density of the radio luminosity function (RLF) for powerful sources, somewhere beyond $z>3$ (Dunlop & Peacock 1990). Detailed identification studies of subsets of various complete radio samples have revealed 2 basic types of EGRS: the 'starbursts' and the 'monsters' (Condon 1989; Jackson & Wall 1999). We also expect to see size and morphology evolution: jets growing from pc to kpc to Mpc scales; and 'spectral ageing' evolution: the steepening of radio spectra with cosmic time, as the electron population loses its more energetic members. Doppler boosting and inclination effects can complicate the interpretation of the data. In more recent times, the observed effects of linear size evolution (Kaiser et al. 1997; Blundell, Rawlings, & Willott 1999), and orientation (Lister et al. 1994) have been studied in detail. The evolving morphologies of powerful, extended, double-lobed radio galaxies (Wan, Daly, & Guerra 2000) have been modelled for the purpose of estimating both intrinsic source parameters (e.g. jet power, density) and also (loose) constraints on the Big Bang (FRW) cos-

Table 1. Basic parameters of selected large radio source surveys.

Survey Acronym	Freq ν GHz	Flux Limit mJy	Sky Region	θ_{resoln} $''$	Radiotelescope	Ref	N_{src}
SKY SCANNING SURVEYS							
3CR	0.18	9000	$-0.5 < \delta < +90$	670	Cambridge790m	Spi85	328
PMN	4.85	20	$-87.5 < \delta < +10$	252	Parkes 64m	Wr96a	50814
GB6	4.85	18	$0 < \delta < +75$	210	NRAO-GB 91m	Gre96	75162
SKY IMAGING SURVEYS							
WENSS	0.33	18	$+29 < \delta < +90$	54	Westerbork4km	Ren97	$\sim 0.3 \times 10^6$
SUMSS	0.84	5	$-90 < \delta < -30$	43	Molonglo1.6km	Boc99	$\sim 0.4 \times 10^6$
FIRST	1.40	1	$\|b\| > +30$	5	VLA-B 12km	Whi97	$\sim 0.9 \times 10^6$
NVSS	1.40	2.5	$-40 < \delta < +90$	45	VLA-D 1.3km	Con98	$\sim 2.0 \times 10^6$
SOURCE IMAGING SURVEYS (ARRAYS)							
JVAS	8.44	60	$-30 < \delta < +90, \|b\| > 2.5$	0.20	VLA-A 36km	Kin99	~3000
CLASS	8.44	20	$0 < \delta < +75, \|b\| > 10$	0.20	VLA-A 36km	Mye01	~13500
MITVLA	8.4,4.9	60	$-40 < \delta < +40, \|b\| > 10$	0.2-0.4	VLA-A 36km	Fl98ab	~12500
PMNATC	8.6,4.8	50	$-87 < \delta < -39, \|b\| > 2$	0.8-1.5	ATCA 6km	Wr96b	8068
SOURCE IMAGING SURVEYS (VLBI)							
PR	5.01	1300	$+35 < \delta < +70, \|b\| > 10$	1-2mas	GVLB 9000km	Pea88	46
CJ1	4.9,1.7	700	$+35 < \delta < +90, \|b\| > 10$	1-10mas	GVLB 9000km	Xu95	135
CJ2	4.99	350	$+35 < \delta < +90, \|b\| > 10$	1mas	GVLB 9000km	Hen95	193
VSOP	4.90	950	$-90 < \delta < +90, \|b\| > 10$	0.3mas	VSOP30000km	Hir00	289

Table 1. Basic parameters of selected large radio source surveys.

mological parameters. Current work typically focuses on interpreting yet larger and deeper samples of radio sources; there is a great need to compile statistically complete samples with essentially complete redshift information (Blundell, Rawlings, & Willott 1999), and this remains a critical "bottleneck" problem that must be solved before further understanding of RLAGNs becomes possible.

What is the physics behind the engines driving AGN phenomena? An up-to-date review on the theories and observations of AGNs may be found in Krolik (1999). Kerr (rotating) BH spacetime is reasonably well understood, at least in the classical limit. However, rotating magnetospheres, accretion disks, fluid and plasma jet dynamics, and radiative transfer are much more complicated, and hence less well understood. Further progress in sorting out this dense web of interwoven physics may only be possible via increasingly sophisticated numerical simulations, which themselves are already very technically complex, though slowly improving (Koide et al. 2000). Analytic formulations of the BH magnetospheric plasma physics are highly idealized, and there are very few specific solutions, even in these simplified scenarios (Beskin 1997). Despite these difficulties, a broad understanding has emerged, and this is summarized schematically in Figure 2. The extreme luminosities of AGNs, and RLAGNs in particular, imply the liberation of a significant fraction of the mass-energy of matter infalling into a central location within the galactic nucleus, at a rate of order $\sim 1 M_{\odot} yr^{-1}$, consistent with Eddington-limited accretion onto supermassive black holes (SMBHs) with M>$\sim 10^6 M_{\odot}$. The Eddington accretion timescale t_{Edd} ~450 Myr is set purely by fundamental constants, and hence all such AGN engines are expected to evolve over similar cosmological timescales; this may be why there is a definite 'AGN Era' (1<z<5). Eddington-limited accretion, continued for just a small number of Eddington times, would leave behind fossil SMBHs as large as $10^8 M_{\odot}$ to $10^9 M_{\odot}$; and, indeed, that is what we are finding in most, if not all, nearby bright galaxies at the current epoch. A very interesting and difficult pair of questions to answer, in future, are: (1) What makes some galaxy centers develop an AGN, and not others? and (2) What makes some AGNs develop into RLAGNs, and not others? Regarding question (1), it seems that there may be a continuum scale in BH mass between active and inactive galactic centers (McLure & Dunlop 2003). It has long been known that only ~10% of optically bright AGNs are also radio-loud. Why are the other ~90% radio-quiet? A possible answer to this key question, involving the fraction of MBHs which are rapidly spinning as a result of galactic mergers, has been suggested (Wilson & Colbert 1995). Piecing together these initial observations and theories, it seems that normal galaxies, radio-quiet AGNs (RQAGNs) and RLAGNs can all be placed on a rough scale based on the central MBH mass M, which seems to be a major determining factor in the resulting physics and observed phenomena. A specific prediction of this speculative theory is the existence of intermediate mass BHs (IMBHs) in galaxy centers; indeed, candidate IMBHs have already been found.

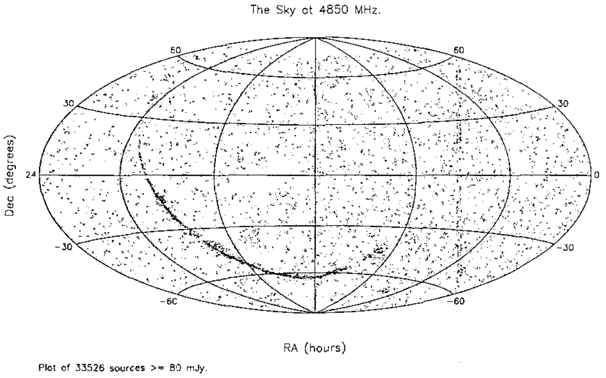

Fig. 3.— All-sky survey plot of ~33,500 discrete radio sources at 4.85 GHz.

III. MIT SURVEYS

The MITVLA snapshot survey (1981-1999) was started with the goal of searching for new radio-loud examples of strong gravitational lenses. From 1979 to 1991, the MIT radioastronomy group made 8 all-sky mapping surveys of radio sources at 4.85 GHz (C-Band), using 2 single-dish radiotelescopes: the NRAO Greenbank 91m to scan the northern hemisphere sky, and the ATNF Parkes 64m to scan the southern. These are known as the MIT-Greenbank (MG) (Griffith et al. 1991), and the Parkes-MIT-NRAO (PMN) (Wright et al. 1996a, b) surveys, which resulted in 8 published catalogs. An all-sky 4.85 GHz plot of ~33,500 radio sources, drawn from the northern NRAO 1987 Greenbank (87GB) survey, and from the southern PMN surveys, is shown in Figure 3. It is clear that the vast majority of radio sources are isotropically distributed in the sky, and hence probably at cosmological distances. In other words, most of the discrete sources in the 4.85 GHz sky map are RLAGNs. Such surveys are then very efficient in finding the 'galactic homes' of a vast population of distant MBHs in our universe.

Based on these relatively unbiased all-sky radio source finding surveys, the MIT group started to hunt for radio-loud gravitational lenses; this was the initial scientific motivation for embarking on the MIT Very Large Array (VLA) snapshot campaigns, for which there have been 4 distinct phases over the 19-yr period 1981-1999: (1) 4,100 northern sky MG sources were imaged at 4.86 GHz in 1981-1986; (2) 3,700 MG sources at 8.44 GHz in 1989-1993; (3) 2,100 southern sky PMN sources at 8.44 GHz in 1991-1995; and (4) 2,600 PMN sources at 8.46 GHz in 1998-1999; making an accumulated total of ~12,500 images. The VLA in its largest configuration, A-array, was used in snapshot mode, with typical integration times of 60–120 seconds. Images were obtained with rms noise of ~0.2–0.4 mJy/bm (S/N>~100) and angular resolution ~0.2-0.4 arcseconds. Typical limiting flux densities of selected sources were 50-80 mJy at 4.85 GHz, and the MITVLA samples are statistically representative, but not complete; the individual snapshot target source lists were chosen roughly in order from bright progressing to faint sources, though many had to be omitted due to time and calibration constraints. The resulting accumulated MITVLA sample cannot be easily defined in terms of complete samples, but since the large majority of radio sources were chosen from initially complete samples, the ~12,500 MITVLA snapshots are expected to be statistically representative, at least for the brighter radio sources. These ~12,500 images form ~30% of the estimated total of ~39,000 sources imaged at arc-second resolution in dedicated VLA and ATCA campaigns over the past 20 years. Only ~1,000 of the MITVLA snapshots have been published so far (Lawrence et al. 1984, 1986). Currently, ~5,000 MITVLA snapshots are readily retrievable from FITS files on DAT tape. Raw VLA archival data for ~9,900 sources are stored on DAT tapes in KAO. Over the next few years, these 9,900 snapshots will be re-reduced in uniform fashion, so that they may be published and made publicly available. For further details on the MIT single-dish and VLA surveys, as well as on the scientific results which have emerged from the efforts of many MIT students over the past 2 decades, refer to the author's workshop paper and thesis (Fletcher et al. 1998a; Fletcher 1998b).

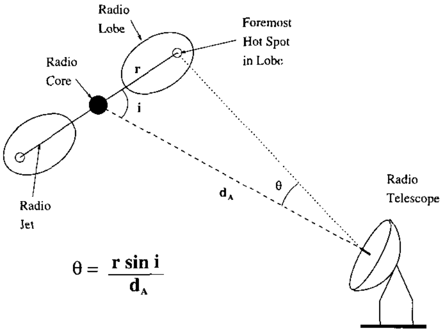

Fig. 4.— A simple model for kpc-jets in extended radio-loud AGNs.

From the finding surveys, the first obvious scientific result that grabs the eye is the remarkably isotropic distribution of EGRS; this has been independently confirmed in many other large-area radio surveys, e.g. NVSS (Condon et al. 1998). From the known redshifts of a small fraction of identified MG-VLA sources, there is evidence for a cosmological distribution of radio emitters ($0<z<4$), which is no surprise. Given this distant population of luminous radio sources, we would theoretically expect ~25 lenses from a complete analysis and follow-up of the MITVLA source sample; so far, 11 lenses have been confirmed, with many more lens candidates still requiring detailed, systematic, follow-up at higher radio resolution, and with ground-based deep optical imaging in good seeing conditions. There is a wide variety of radio morphologies seen in the VLA snapshots; and a systematic classification system, based on the first ~1000 MITVLA sources reduced, has been published (Lawrence et al. 1984). There is also a broad distribution of 'largest angular sizes' (LAS) for the extended radio sources, with a clear majority of relatively small angular size sources ($\theta < 5''$). The MITVLA LAS histogram may be used to place limits on their jet advance (i.e. lobe propagation) speeds (Section IV).

Optical identifications have been published for the first ~1,000 MITVLA sources, and attempted for a further ~2,500. Typically, ~40% of MITVLA sources can be detected to a limiting magnitude of ~20 in the optical POSS plates or the Digitized Sky Survey (DSS). As a general rule, bright, flat-spectrum sources are the easiest to identify optically. A sample of ~120 compact, double-lobed radio galaxies (with angular sizes $0.2'' < \theta_{LAS} < 2.0''$) were extracted from ~4,200 snapshots. These were found to be mostly steep-spectrum radio sources, and hence members of the Compact Steep Spectrum (CSS) class. Deep BVRI imaging to a limiting magnitude R~22, at the MDM 1.3m and CTIO 1.5m, shows these to be red in color; a few spectra reveal low to intermediate redshifts. These MITVLA CSS sources are probably young galaxies, intermediate in size, and probably in evolutionary development, between the ultra-compact VLBI sources and the 'classical' 3C/4C double-lobed radio galaxies.

There are numerous potential uses and discoveries made possible by the MITVLA database, as well as by similar RLAGN image databases (e.g. JVAS, CLASS & PMNATCA), once they are publicly released: new radio calibration sources; new gravitational lenses; new additions to specific classes of RLAGNs: such as CSS, GHz-Peaked Spectrum (GPS), high-redshift as well as 'distorted' radio galaxies and quasars. The ~39,000 snapshot images accumulated to date form an indispensable scientific complement to the lower resolution data in the single-dish and sky scanning interferometer surveys (FIRST, NVSS, WENSS & SUMSS), as well as to the ultra-high-resolution VLBI surveys aimed at the central pc-scale cores and jets of RLAGNs.

IV. KILOPARSEC-JET ADVANCE SPEEDS

A unique contribution from the MITVLA snapshot surveys is the compilation of the 'largest angular size' (LAS) histogram for a spectrally unbiased sample of radio sources (this is not possible for the larger JVAS/CLASS sample of compact, flat-spectrum selected sources). This statistical distribution may be used to set (model-dependent) limits on the growth rate of extended radio structures on kpc-scales, as detailed in the author's workshop paper and thesis (Fletcher et al. 1998a; Fletcher 1998b). Here, we should be careful to distinguish between the jet head propagation speed $v_{head} = \frac{dR}{dt}$, and the jet fluid flow speed v_{jet} (these are related by the momentum transfer between the jet fluid and the ambient medium). In general, we expect $v_{head} \leq v_{jet}$. A simple geometrical model may be assumed to apply to the extended radio sources in the sample, as shown in Figure 4.

Various assumptions were made in order to put limits on the jet propagation speed for the MITVLA radio sources: (1) continuous jet outflow (not episodic); (2) uniform distribution of jet ages, with maximum age set by $\sim t_{Edd}$; (3) isotropic distribution of kpc-scale jet axis inclination angle i; (4) Doppler beaming effects are small for pole-on sources (small i); (5) strong cosmological evolution (most sources at z~1); (6) various FRW cosmologies ($q_0, H_0, \Lambda = 0$); (7) no instrumental angular bias between $0.''3 - 120''$; and (8) statistically representative sample of MITVLA sources. The major theoretical assumption is that kpc-jets are continuously driven by MBHs accreting at close to the Eddington rate, with maximum age set by t_{Edd} ~450 Myr, *independent of mass.* Statistically, we expect the jets to have an average length of about the average lobe propagation speed $< v_{head} >$ multiplied by the average jet lifetime $< t >$.

A jet advancing at speed v~c, for half an Eddington lifetime t~225 Myr, placed at a typical cosmological distance D~1 Gpc, will subtend an angle of about ~4 degrees. However, the median angular size from Figure 5 is about $4''$, which is 3–4 orders of magnitude smaller! This strongly constrains the average jet advance speed to be in the range $0.0002 < v_{head}/c < 0.1$, with >90% confidence. The main caveat is that if the isotropy and jet continuity assumptions fail, the MITVLA LAS histogram gives limits on projected distance only (~0.22 Mpc for >95% of MITVLA sources). Given this upper limit, relativistic jets could "squirt" for up to ~1 Myr, over kpc scales, and many such "squirtings" could occur in a few Eddington BH lifetimes. Interrupted flows are indeed seen in the 'double-double' radio galaxies, but these are relatively rare cases.

If the kpc-jets are as ultra-relativistic as the VLBI jets, with $\Gamma >\sim 5$, then Doppler boosting would be important for i<35 degrees (~18% of an isotropic population). They would dominate any flux-limited sample, and highly asymmetric sources would then be expected to be the norm. The arm length ratio asymmetries would be as high as ~10, which is *not* observed. This still leaves room for mildly relativistic jets, though.

What does all this mean? From other work, we know that both pc-scale and kpc-scale jets (e.g. in 3C273 and M87) show superluminal, or at least mildly relativistic, moving features. However, these relativistic flows probably arise from the bulk motion of jet fluid v_{jet}, and not from a jet advance or "pattern" speed v_{head}. Previous work on the arm length asymmetries of collinear double radio sources, and using 'spectral ageing' anal-

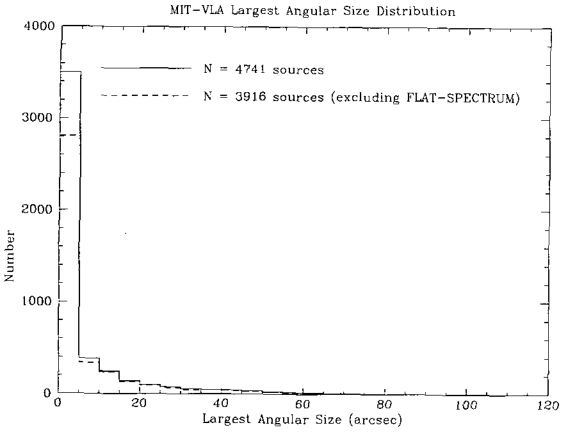

Fig. 5.— Largest angular size distribution for ~4000 MITVLA survey sources.

yses of the electron populations near the terminal hot spot 'backflow' (Liu, Pooley, & Riley 1992), all place firm statistical limits of ~0.2–0.3c on the jet head advance speed v_{head}. More recent work has considered the observed asymmetries and Doppler beaming effects arising from initially relativistic jet bulk flow motion. These show that there is significant deceleration of initially relativistic flows, as they emerge out onto the kpc-scales. Furthermore, we theoretically expect v_{head} to be less than v_{jet}. Due to momentum transfer, the relativistic pc-scale jets may become non-relativistic on kpc scales. In the case of 'heavy' jets ($\rho_{jet}/\rho_{amb} \gg 1$), v_{head} may become comparable to v_{jet}, and so the flow speed is then definitely not relativistic: $v_{jet}/c \ll 1$. This may be true for the 'edge-darkened', subsonic FR I jets. However, if the jets are 'light', then it is quite possible, though by no means certain, that the flow speed is relativistic. This may be the case for the 'edge-brightened', supersonic, FR II jets. There may then be a connection between jet speed and morphology; a theory has been proposed that links the kpc-scale morphology to the inner workings of the central engine and its outflow, operating via a 'magnetic switch' mechanism (Meier et al. 1997). However, no strong observational constraint on the flow speed v_{jet} is possible, without independent knowledge of the jet density contrast with the ambient medium. In the future, more attention needs to be paid to potentially revealing connections like these. In particular, the correlation between radio source age, morphology and jet dynamics needs to be more fully investigated and clarified. The main lesson to be learnt is that we can now start to relate statistical distributions of observable RLAGNs parameters to the physics of their central engines.

V. BLACK HOLE PHYSICS

AGNs range over many orders of magnitude in time, space, wavelength, power and energy. This attests to the fact that the observed phenomena come from a complicated, interwoven network of physical processes operating over both small and large regions, and over short and long times. The causal progression of physical phenomena in RLAGNs is clear: black hole; magnetosphere and accretion disk; pc to kpc to Mpc jets; hotspots; lobes & bridges; then the IGM. The connection between theories and observations starts with the physics of the growth and evolution of the central MBHs. In modelling the growth and evolution of AGNs, we must start off with the formation and physics of the central MBH; we focus specifically on the MBH here.

Classical general relativity is well understood for Schwarzschild and Kerr-Newman BHs. It is believed that rotation and magnetic fields are essential for extracting power from the BH (Blandford & Znajek 1977). What is required is to model the Kerr BH plasma magnetosphere, as well as the magnetized, turbulent accretion disk, and the launching of the VLBI pc-scale jet at its base. This is far from easy, and many simplifying assumptions still continue to be made, even in recent theoretical and computational research: 1) single-component plasma; 2) quasi-neutral plasma; 3) axisymmetry; 4) magnetic forces dominate inertial ones (inertia free); 5) infinite conductivity (ideal-MHD conditions: 'frozen-in flux'); 6) degenerate electromagnetic fields (which cannot exist in charge accelerating 'gaps'); 7) (Lorentz) force-free; 8) (time) stationary; and 9) Newtonian regime.

In the past, almost all studies of the plasma magnetospheres of compact objects have retained all assumptions 1–9 above (in particular: axisymmetric, stationary, ideal-MHD plasma physics in the Newtonian regime). This is quite natural as a first step towards a broad understanding of the problems involved. However, it is a foregone conclusion that many of the results of these preliminary attempts will be largely inapplicable to real accreting MBH systems.

The 'Blandford-Znajek' (BZ) black hole magnetospheric power extraction process (Blandford & Znajek 1977) was one of the first analytic attempts to define a general relativistic theory for axisymmetric, stationary, ideal-MHD, BH magnetospheres. Since then, there have been many analytic refinements made (Macdonald & Thorne 1982; Thorne, Price, & Macdonald 1986) based on this initial physical idea. For a recent review of axisymmetric, stationary, ideal-MHD, analytic models of BH magnetospheres and outflows, see the review by Beskin (1997).

It is a well-known fact that the luminosity output of AGNs can be variable in time, over many different timescales (Ulrich, Maraschi, & Urry 1997). If these obvious variabilities are driven by central MBH physics, then it is very likely that the power extraction from the central MBH cannot be time stationary. The first time-dependent, analytic models for axisymmetric, ideal-MHD BH magnetospheres (Park & Vishniac 1989) were proposed in 1988. The long-term, secular (i.e. cosmological) evolution of accreting MBHs in AGNs was analyzed by Park & Vishniac (1990). The general theme of time-dependent AGN MBH magnetospheres, disks and outflows, and how they may cause the observed time variability in AGN luminosity, has been addressed by Park (2000). There have been further attempts to drop more assumptions, such as axisymmetry, together with stationarity, but the resulting theory seems no more approachable than before. It seems that the future pursuit of a more realistic understanding of these inherently complex physical scenarios must be continued by way of numerical simulations.

To better understand RLAGN variability in the core region, we will have to first understand time-dependent plasma physics phenomena, such as: magnetic reconnection, coronal magnetic ejections, dynamo theory and winds. Axisymmetric simulations (2.5D) have been performed for Kerr BH magnetospheres (Koide et al. 2000; Meier, Koide, & Uchida 2001), assumed force-free. These have indeed developed jets along the polar axis, after some ~100 dynamical rotation periods of the central BH. There also appear 'Torsional Alfven Wave Trains' (TAWTs), which seem to be important in the transport of plasma, magnetic field and angular momentum away from the hole, magnetosphere and disk. Such a steady, magnetic 'helix' seems to be a persistent and generic feature in many of the recent simulations. A 'magnetic switch' mechanism (Meier et al. 1997) may determine the jet speed in RLAGNs; if real, this may be an important physical mechanism which affects the radio source morphology on much larger (kpc) scales. For the latest developments in the rapidly growing area of BH GRMHD physics, theories, simulations, and their relation to observations, see: Chang et al. 2001; Punsly 2001; Lee & Chang 2002; Lee & Park 2002.

The last 4 assumptions (6-9) above have each been dropped in various papers, but not all together at the same time. An important one to shed is *stationarity* for the BH magnetosphere; this is especially critical, in view of the fact that AGNs are known to be variable in their observed properties, over all timescales from years down to minutes. The analytic formalism developed first in 1989 (Park & Vishniac 1989; Park 2000), for axisymmetric, *non-stationary*, ideal-MHD, force-free Kerr BH magnetospheres, has since been reclarified and recast into an improved set of equations, and the associated 'Transfield Equation' has been derived (Park 2002a, b).

As an example of a preliminary result from this non-stationary analysis, the steady-state BZ power output has been calculated as the time stationary limit of the general non-stationary case. The original (1977) BZ power output formula was found to be $P_{BZ,stat} \propto x(1-x)$, whose value is determined by the sole parameter $x = \Omega_F/\Omega_H$, the ratio of the magnetic field and BH angular velocities. However, the steady part of the *non-stationary* power output has a dependence on an extra parameter, the radial infall velocity at the BH horizon: $y = -v_{rad}/c$. The dependence on a 2nd parameter y is clearly shown in Figure 6. The derivation of these results is based on the same equations that yield the new 'Transfield Equation' for axisymmetric, non-stationary BH magnetospheres (Park 2002a, b). There is a divergence to unphysical (negative) power output for large values of the infall velocity $y > x$; this can only be avoided if the angular velocity ratio $x \to 1$, in which case the radial infall velocity will approach the expected free-fall limit c. What this means is that the magnetic field lines fall onto the BH horizon at the speed of light; and, at this point, the angular velocity of the hole and the field should be equal $(\Omega_F/\Omega_H)_{horizon} \to 1$. If this condition is not met, it seems that the power output would assume unphysically divergent negative values. Hence, it is suggested that the appropriate boundary conditions near the horizon are that: $v_{rad}/c \to -1$, and that $(\Omega_F/\Omega_H)_{horizon} \to 1$.

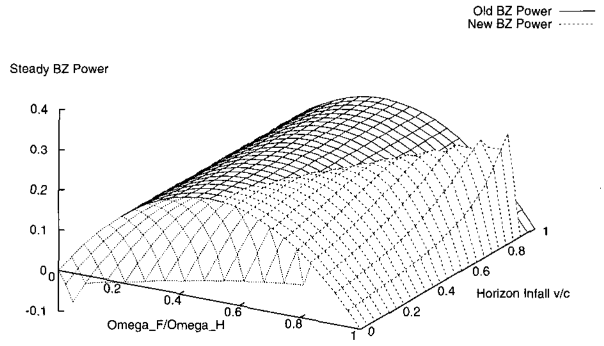

Fig. 6.— *Comparison plot of the steady component* of the Blandford-Znajek (BZ) power output from a *non-stationary*, axisymmetric, force-free, ideal-MHD, Kerr black hole magnetosphere (the surface drawn with dashed lines), with the corresponding BZ power for the time-stationary case (solid lines). The independent variables are the ratio of the magnetic field to black hole angular velocity, and the plasma radial infall velocity (normalized to the speed of light, c); power is plotted in arbitrary units.

From this axisymmetric, *non-stationary* analytic model, it is suggested that there is 'no slip' between the field and the horizon ($\Omega_F = \Omega_H$). However, this may only be possible under the assumed ideal-MHD conditions. On the other hand, the original (stationary) BZ result that there be *zero* power for $\Omega_F = \Omega_H$ seems unnatural, and is in any case expected to change within a more realistic, *non-stationary* analysis. This suggested 'no slip' condition for the BH magnetic field says nothing about its behaviour away from the horizon; indeed, we generally expect Ω_F to decline towards the Keplerian accretion disk velocities, as one progresses further away from the event horizon.

A critical set of questions still outstanding in the entire investigation into AGNs in general, is concerned with: (1) how MBH "seeds" form, (2) how they grow to super-stellar mass, and (3) how their physical evolution

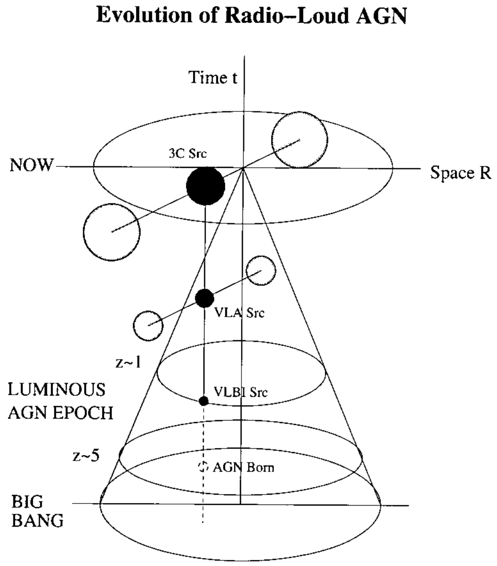

Fig. 7.— Spacetime evolution of MBHs and their jets in radio-loud AGNs.

is related to that of their host galaxies. Somehow, the answers to these questions are related to the recently discovered 'BH mass vs. bulge luminosity' and 'BH mass vs. central velocity dispersion' relations; these strong correlations have been observed to occur in both active and inactive galaxies (McLure & Dunlop 2003), which may imply a simple, unified formation scheme for MBHs in all types of galaxies. If these current speculations about the observations prove to be correct, then we may be seeing a first hint that there is actually a continuum connecting normal bright galaxies to RQAGNs to RLAGNs; and that the main governing parameter determining the physical properties and evolution of their central regions is the mass M of the central MBH. However, at this point, this last suggestion is still a pure speculation.

In summary, much more work is required to understand these complex MBH physics. In general, the astrophysics of MBH growth and evolution needs to be much better understood (convenient assumptions need to be removed from the analytical theory, and more realistic simulations need to be done). Many of the BH high energy plasma physics processes also occur in other accreting compact systems, even though the details may be different. It may be very rewarding to try to apply lessons learnt from one type of highly energetic system, to another of a similar nature. For example, 'magnetic reconnection' in the BH magnetosphere and accretion disk will need to be investigated; perhaps, for this piece of the puzzle, inspiration can be drawn from the abundant observations of plasmas in the Sun, and elsewhere in our solar system.

VI. FUTURE WORK

In the case of observations, high-resolution images of RLAGNs from the MITVLA and other (CLASS, PMNATCA, VSOP) surveys should be published, and made publicly available, over the next few years. Attention needs to be paid to the statistical completeness of these large RLAGN samples. While not all of them may be complete, suitably chosen subsets of them may be reasonably complete, so these subsamples could be used for statistical analyses (as long as they are large enough). Searching for statistically complete radio imaging samples will become possible once more of these images are made available. Optical identifications need to be attempted for radio component positions drawn from high-resolution interferometer imaging. This is possible with online Internet databases, such as DPOSS, DSS, APS, APM and (SUPER)COSMOS. Cross-identifications with non-optical surveys (e.g. IRAS, ISO, ROSAT and EGRET) will also be necessary to constrain RLAGN physics, via the compilation of spectral energy distributions (SEDs). The NASA Astrophysics Data Archives will be especially useful in this regard. Over the past decade, there has been an explosion of Internet web browser usage, and one of the results of this new phenomenon has been the creation of prototype 'Virtual Observatories'. The US Decadal Review recommendations for 2000–2010 proposed a National Virtual Observatory (NVO) along these lines, and an International Virtual Observatory Alliance (IVOA) is now being set up (http://www.ivoa.net). Even today, the available Internet astronomical resources are vast (Kidger, Pérez-Fournon, & Sánchez 1999), though mostly still not organized for truly automated processing. The redshift sparsity problem for RLAGNs may be solved by wide-field fiber spectroscopy (e.g. using 2dF, 6dF) or, better and more easily, by reaping photometric redshifts, if possible from a large-area optical survey such as SDSS. Where data are gathered on the optical counterparts of RLAGNs, the selection effects would need to be accounted for in the statistical modelling of the joint radio-optical observation selection process. Finally, for RLAGNs, the long-term evolution of their radio luminosities and jet lengths may be derived from their estimated luminosity functions (LFs), and linear size functions (SFs), once the redshifts become available for sufficiently large, and reasonably complete, samples (Blundell, Rawlings, & Willott 1999).

In the case of the theories, many clues and insights should be forthcoming from a detailed, global consideration of all the large, statistical samples and high-resolution images of RLAGNs which will become publicly available over the next few years. To understand the physical behaviour of the growth and evolution of the MBHs, and their derivative radio structures, detailed, global Monte-Carlo physical modelling of the population of individual AGN sources is required. Many various individual aspects of RLAGN population modelling have already been proposed in the literature, for: MBHs, accretion disks, pc-scale jets, and especially the kpc-scale jets & lobes (Blundell, Rawlings, & Willott 1999; Lister et al. 1994; Wan, Daly, & Guerra 2000). Bearing in mind the central role played by growing and accreting MBHs, there are clearly identifiable functions for which physical models need to be proposed. Some of the more important ones are the following (here, a is the normalized BH spin, and we are careful to distinguish between the 'cosmic' time τ and the source 'lifetime' t):

- Creation Rate of Galaxies, $C_{gal}(\tau)$;
- Creation Rate of MBHs, $C_{mbh}(M, a, \tau)$;
- Time-dependent MBH Mass Function, $\Phi_{mbh}(M, a, \tau)$;
- Rate of Change of MBH Mass, $\dot{M}(M, a, t)$;
- Power Output, $P(M, a, t)$;
- Radio Luminosity, $L_{radio}(M, a, t)$;
- Jet Propagation Speed averaged over kpc scales, $< V_{head}(M, a, t) >$.

All of these need to be put into Monte-Carlo models of the evolving population of MBHs and their derivative structures. Figure 7 is a schematic diagram showing the basic idea behind this proposal. Time permitting, a basic model will be attempted along these lines, after the reduction and analysis of the MITVLA snapshot survey data is completed. To help set up suitable simulations, an important ingredient will be the modelling of the long-term evolution of the MBH population and their associated physical parameters (M, a, t); as well as of the radio luminosity output, and the dimensions and morphologies of the jets and lobes. The basic theories set out in certain papers addressing these long-term evolutionary processes (e.g. Kaiser et al. 1997; Park & Vishniac 1990) will serve as indispensable starting points from which to explore possible theoretical interpretations of the large body of available data on radio-loud AGNs.

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