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Introduction and Historical Perspective

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Definition: In this book, the term "relativistic jet" designates highly collimated outflows from supermassive black holes, or in more general terms from a "central engine" in the centers of active galactic nuclei. The jets transport energy and momentum from the central engine to remote locations. In some sources, energy and momentum are dissipated in hot spots hundreds of kiloparsec away from the galactic nucleus and in radio lobes which surround the jets and the hot spot complexes.

1.1
A Brief History of Jets

Jets are collimated outflows associated with supermassive black holes (SMBH) in the nuclei of some types of active galactic nuclei (AGN). The first recorded observation of a jet was in 1918 within the elliptical galaxy M 87 in the Virgo cluster: "A curious straight ray lies in a gap in the nebulosity in p.a. 20°, apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is 11″ from the nucleus" [1]. At that time, the extended feature was a mere curiosity and its nature was not understood. It was not until well after World War II, when technical improvements provided for increasingly better angular resolutions and lower noise receivers, that it was demonstrated that many galaxies exhibited extended radio emission consisting of a nuclear component, jets, hot spot complexes, and radio lobes. Implementation of radio interferometry developed quickly during the same period. In particular, so-called Very Long Baseline Interferometers (VLBI) showed that there were compact high-temperature radio cores in AGN.

According to our current understanding, jets originate in the vicinity of a SMBH (with several million to several billion solar masses) located at the center of the AGN. The jets are powered by these black holes and possibly by their associated accretion disks, and the jets themselves transport energy, momentum, and angular momentum over vast distances [2–4], from the "tiny" black hole of radius $r = 10^{-4} M_{\rm BH}/10^9\,M_\odot$ pc to radio hot spots, hot spot complexes and lobes which may be up to a megaparsec or more away. Thus the study of jets must encompass a

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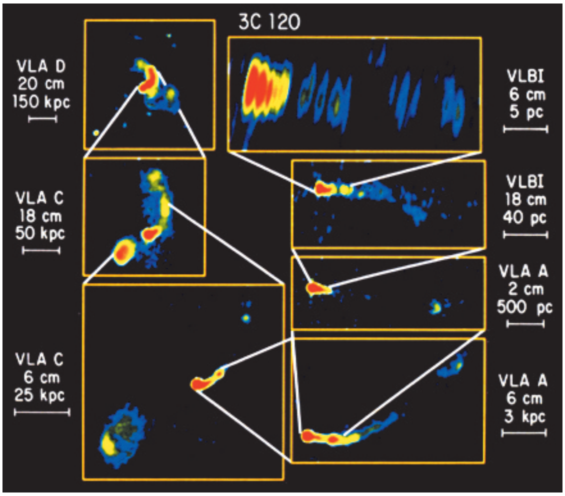

Figure 1.1 This montage of radio observations of 3C 120 demonstrates the range of physical sizes (projected of course), the knotty behavior (common to most jets), and quite pronounced bending (not a universal property of jets). "Knotty" is a somewhat poorly defined description, but essentially means that jets usually have regions of high brightness interspersed with low-brightness segments: often so low that these segments are not detected. The apparent bending of a jet does not mean it bends that much in 3D since if the jet is coming towards us a physically small bend may be sharply amplified in projection. This figure is a "false-color" version with red indicating the highest brightness and blue the lowest. It first appeared in Harris, Mossman, and Walker [5]; reproduced with permission from the National Radio Astronomy Observatory.

range of scales covering a factor of 10^{10}! Some sense of this vast range of scales is provided by Figure 1.1.

It is not yet known what jets are made of and which of the components (atoms, protons, electrons, positrons, Poynting flux) carries the dominant fraction of the jet energy and momentum. In a similar fashion, it is not firmly established how jets form and accelerate and what collimates them over vast distances.

1.1.1
Synchrotron Emission as the Primary Process for Continuum Radio Sources

During the 1950s, a fascinating interplay between theory and observation led to key advances in our understanding of the nature of continuum radio sources. When discrete cosmic radio sources were first observed, the general notion was to interpret them as radio stars since it was already known that the Sun produced radio waves. Thus as early as 1950, Alfvén and Herlofson [6] suggested that the radio emission of the object Cygnus A (which we know call a radio galaxy) could be interpreted as synchrotron radiation from cosmic ray electrons gyrating in a star's magnetic field. A few years later, Shklovsky [7] championed the idea that both the radio emission and the optical light from the diffuse component of the Crab Nebula – a supernova remnant in our Galaxy, were segments of the same synchrotron spectrum. With detections of optical linear polarization from both the Crab Nebula and from the jet in M 87 [8], the community was quickly convinced that synchrotron radiation was the primary emission mechanism for the ever-increasing number of continuum radio sources. Theorists were soon publishing plausible physical parameters for synchrotron models for the radio and optical nonthermal emissions, for example Burbidge [9] for the AGN M 87 in the nearby Virgo galaxy cluster.

1.1.2
Occurrence/Ubiquity of Radio Jets

The discovery of radio emission from extragalactic jets began with the identification by [10] of "a star of about thirteenth magnitude and a faint wisp or jet" near the accurate radio positions of two bright components of 3C 273 derived from a lunar occultation observation [11]. Schmidt's identification of 3C 273B and the measurement of a cosmological redshift of $z = 0.158$, which implied an extragalactic origin, famously marks the start of the quasar "industry".

His identification of 3C 273A with the tip of the "faint wisp or jet" also marks the start of a radio jet industry that grew more slowly. The next step came when the work in [12] showed that a compact extranuclear radio component in 3C 274 coincided with the brightest knot in the optical jet of the object M 87, but it was not until the one-mile and five-kilometer interferometers at Cambridge began systematic high-resolution studies of 3C sources that further radio jets were found in the low-power plumed source 3C 66B [13] and in the higher-power "classical double" 3C 219 [14]. Radio jets were soon recognized in images taken with the Westerbork Synthesis Radio Telescope of other low-power radio galaxies: B0844+319 and 3C 129 [15] and retrospectively in 3C 449 [16] and 3C 83.1 [17].

The first example of an AGN radio jet remaining well collimated and evidently stable over several hundred kiloparsecs was found in the giant radio galaxy NGC 6251 [18]. These early discoveries showed that the jet phenomenon ran the gamut of radio powers and structure types, but it remained unclear whether the sources with detected radio jets were in some sense exceptional. That question was answered when the Very Large Array (VLA) came into operation in the late 1970s. Radio jets were soon found in radio-loud AGN of all known sizes and powers, including Seyfert, classical radio galaxies, and quasars. The VLA was able to show the *ubiquity* of radio jets because its 27-element design provided the sensitivity to detect weak jets in only brief observations, the dynamic range to do so in the presence of bright unresolved emission from the AGN, and the angular resolution to separate jets convincingly from other extended radio emission. This allowed simple but well-defined quantitative criteria to be applied for identifying a linear radio feature as a "jet" [19, 20].

The mass and luminosity range of objects known to generate relativistic jets was also extended to include the galactic "microquasars", for example SS 433 [21] and 1E140.7-2942 [22].

1.1.3
Origin of the Notion that SMBHs Reside in All Galactic Nuclei

It was not long after the realization that radio galaxies (which roughly account for $\approx$ 1% of all galaxies, and favor massive ellipticals) produce jets, which transmit prodigious amounts of power out of the central region, that it was also understood that jets had to be coupled with processes involving a black hole of high mass, that is, more than a million solar masses [23]. The two available sources of energy to power jets and thus hot spots and lobes are potential energy (in the gravitational field of a SMBH) and rotation of the SMBH itself. Furthermore, the role of AGN in influencing galaxy formation and evolution was recognized quite early (e.g., [24]). As other developments established a relationship between the properties of galaxies and the masses of their black holes [25, 26], a great deal of effort was expended on trying to ascertain why some galaxies and quasars are radio-loud, whereas others are radio-quiet ("quiet" is a relative term, which indicates a bimodality in the distribution of the ratio of radio intensity to optical intensity rather than a complete absence of radio emission).

1.1.4
Working Out of Relativistic Effects

Perhaps the most important development after the realization that jets carry power over vast distances and that the emission we see is nonthermal came from Very Long Baseline Interferometry (VLBI), see Section 5.2. After primitive radio interferometry demonstrated the basic source structure of extragalactic radio sources [27], astronomers developed VLBI techniques in which phase information was sacrificed in order to obtain baselines which were too long to be coherently connected. Thus the order of the day was to develop more stable atomic clocks and more reliable and higher-density magnetic tape drives so as to record wider bandwidths. Since almost all radio sources have emission on both sides of the nucleus, but a majority of bright jets are on one side only (Section 5.2.1), the notion of "Doppler boosting" became the established paradigm. As the VLBI data improved, it became apparent that individual emission regions at the parsec scale could be tracked and had apparent proper motions larger than the velocity of light. This effect was quickly explained as a bulk relativistic motion of an emitting plasma moving close to our line-of-sight (Section 5.2.5). Most of the salient relativistic effects pertaining to jets were worked out in Konigl's thesis [28].

1.1.5
Microquasars

"Microquasars" is a term applied to those galactic X-ray binary systems that have been found to eject luminous material, which appears to be moving at a considerable fraction of the speed of light. In one case (SS 433) the material traces out a helical path and emission lines of ionized common elements have been found in the optical and X-ray spectra. A detailed precessing jet model provides an accurate value of the velocity: $0.26c$. In addition to the spectral lines, there is a continuous spectrum of synchrotron emission so VLBI techniques have augmented the optical and X-ray study of line emission with direct imaging of the twin jets.

No line emission has been observed for any other galactic microquasar, nor for any extra galactic jet, large or small. Although many researchers have attempted to demonstrate that microquasar jets and AGN jets are basically the same (physical) phenomenon, there are significant differences. Chief among these is the difference in velocity of ejection. While some microquasars have features believed to be moving at 0.8 or $0.9c$, we always see both sides of the jet whereas for AGN jets, Doppler boosting often enhances the approaching jet and the receding jet is below detection thresholds.

The study of X-ray binaries and their jets has led to a vast amount of published literature and the classification of many aspects of their behavior. In this book, we will not attempt to deal with these jets as such, but refer to them from time to time if relevant. Interested readers can consult [29].

1.2 Jets at Optical, UV, X-Rays and γ-Rays

At the higher frequencies, the synchrotron E^2 half-lives are on the order of several years in typical fields of 0.1–1 mG. Since we have optical polarization from many jets and, at least in the case of knot HST-1 in the M 87 jet where we have strong variability at all wavelengths, we are confident that the high-frequency radiation from some jets comes from synchrotron emission. This translates into the fact that every emission region must also be an acceleration region.

1.2.1 HST Optical/UV Jets

During the latter part of the 1900s, there were several ground-based studies of the brightest optical jets. These efforts were plagued by limited angular resolution (poor seeing) and often resulted in ambiguous results with respect to spectral properties and degree of polarization.

The quasar jet 3C 273 was almost as bright as the M 87 jet, and did not have to contend with the optical light of the encompassing galaxy, and thus was an obvious target. Therefore, once the Hubble Space Telescope (HST) was repaired, detailed morphology, robust polarization data and spectral properties could be obtained. Figure 1.2 shows a comparison of the relative brightness distributions for three different bands.

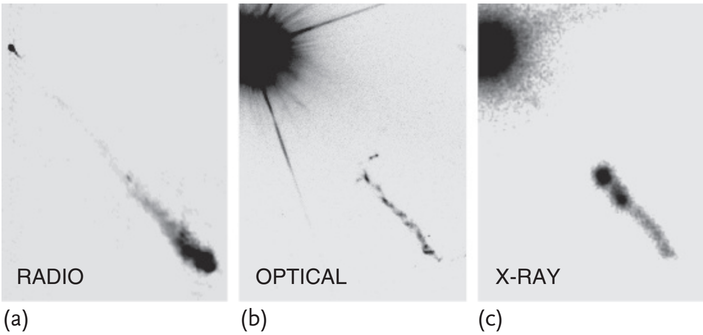

Figure 1.2 The famous jet of the quasar 3C 273. (a) The radio panel is from the MERLIN archives at a frequency of 1.6 GHz; (b) the optical is from the Hubble Space Telescope at 6000 Å; and (c) the X-ray image is from a set of observations made by Chandra. It is filtered for the energy band 0.3–6 keV and has been slightly smoothed. The distance from the quasar (upper left) to the tip of the jet is 22.3″ which corresponds to 60 kpc (in projection) at the distance (750 Mpc) of this quasar. The large apparent diameter of the quasar in the optical and X-ray images is an instrumental effect caused by the low-level wings of the point spread functions. Note how the jet is almost invisible for quite some distance before abruptly appearing with a very bright X-ray knot which is weak in the radio. Although there are some "wiggles", this jet is basically straight, unlike that of 3C 120 (Figure 1.1).

1.2.2
X-Ray Jets

The Einstein Observatory, launched in 1978, was the first device that had sufficient angular resolution ($\approx 5''$) and sensitivity to detect X-ray knots and hot spots associated with jets. *ROSAT* (launched in 1990) had similar capabilities; both satellites had microchannel plate detectors in addition to the proportional counters. So, with some concerted effort, a handful of jets had been detected before the launch of Chandra: the hot spots of Cygnus A and the jets of Cen A, M 87, and 3C 273.

With the advent of Chandra with its much improved angular resolution ($\leq 1''$), many more jets were detected. The early "surveys" targeted the brighter radio jets thought to be close to our line-of-sight, and of course the first detection was achieved by chance: the quasar PKS 0637 was thought to be a bright unresolved source and was chosen as a target for focusing the mirrors (i.e., determining the best position for the detectors; see Section 7.2.1).

X-ray data on knots and hot spots have provided key insights into several facets of jet physics. If the X-rays from a particular feature are dominated by synchrotron emission, Lorentz factors of the radiating electrons, γ of order 10^7–10^8 are required in the nominal fields on the order of hundreds of microgauss (μG). These extremely high-energy electrons have short half-lives and so are more restrictive than the optical data as to how large a source can be in the sense of how far these electrons can travel from their acceleration site. Additionally, the ability to estimate physical parameters for these very high-energy electrons provides insights into loss mechanisms and high-energy cutoffs in the electron distributions.

Another aspect of these X-ray detections came from the hot spots of FR II radio galaxies. It was shown that synchrotron self-Compton (SSC) emission provided a good model for the X-ray intensities observed from the high-brightness radio hot spots of the radio galaxy Cygnus A. Since the photon energy density could reliably be measured from the observed radio spectrum and the (resolved) source size, it was possible to estimate the average magnetic field strength without first assuming equipartition. While this represented an important advance, many more sources with hot spot detections have become available, and of these, only a relative few match the SSC predictions as well as the example of Cygnus A.

The case of X-ray emission from the knots in the jets of FR II radio galaxies and quasars is still a topic of debate. Since there appears to be a high-frequency cutoff in the optical for many knots, it was difficult to fit a simple synchrotron spectrum to the radio-optical-X-ray data. A relatively simple model was advanced [30, 31] to overcome this difficulty: the X-rays were identified as the result of inverse-Compton scattering between the relativistic electrons and the photons of the microwave background. To get enough intensity from this process it is necessary to assume that the bulk Lorentz factor of kiloparsec-scale quasar jets are on the order of 10 or greater in many cases. Further, it turns out that very low-energy electrons (i.e., γ on the order of 100) are those that produce the observed X-rays and therefore, one must rely on a blind extrapolation of the electron spectra from the typical energies of several thousand (estimated from centimeter radio data) down to a few hundred or less. This is usually performed by assuming the observed radio spectrum can be extrapolated down to a MHz or so without any cutoffs or breaks (see Section 7.5.5).

1.2.3 Jets in γ-Rays

While jets in AGN can often be resolved on parsec and larger scales, most radio-loud AGN possess bright cores on subparsec scales, which are spatially unresolved. It is commonly believed that γ-ray emission, present in a special class of radio-loud AGN called blazars, is produced in this unresolved core region. One of the major surprises of the EGRET experiment on board the satellite-borne Compton Gamma-Ray Observatory (1991–2000) was the discovery that high-energy (100 MeV up to a few GeV) γ-ray emission is a common property of blazars, and that power emitted in the γ-ray band typically surpasses the power emitted at longer wavelengths. At even higher energies, ground-based experiments can detect γ-rays in the TeV energy range. Pioneering observations with the Whipple Cherenkov Telescope between 1992 and 1996 showed that some blazars (e.g., Mrk 421) are not only sources of extremely energetic TeV γ-rays, but that the TeV emission shows time variability on extremely short ($\sim$ min) time scales. The fast flux variability constrains (via causality arguments) the size of the emission region. The fact that TeV γ-rays are observed and are not absorbed in $\gamma\gamma \rightarrow e^+e^-$ pair production processes of TeV γ-rays interacting with IR and optical photons leads to the conclusion that the jets have to be highly relativistic with bulk velocities exceeding 99%

of the speed of light (see the discussion in Section 3.2.1.2). Modeling the broadband radio to γ-ray energy spectra of TeV-bright blazars indicates even higher jet velocities: 99.98% of the speed of light. Intensive observational campaigns involving a large number of ground-based and spaceborne observatories have resulted in rich data sets with detailed information about the time dependence of the broadband energy distributions. The blazar phenomenon will be discussed in detail in Chapter 8.

1.2.4
Gamma-Ray Bursts

Gamma-ray bursts (GRBs) have been known for almost 40 years as short flashes of γ-rays which dominate the entire γ-ray sky for durations of $\lesssim 1\,\mathrm{s}$ to a few minutes. With the successful operation of the Italian-Dutch BeppoSAX satellite in the late 1990s, it became possible to associate GRBs with afterglows at longer (X-rays, optical) wavelengths. This also allowed for the determination of redshifts of their counterparts, establishing that these sources must be extragalactic. Once the distance to a GRB is known, one can convert the observed γ-ray flux into a luminosity, assuming that the γ-rays are emitted isotropically. This calculation yielded total released energies up to $\sim 10^{54}$ erg, that is, surpassing the typical radiative energy release of a supernova by a factor of ~ 1000. The fast flux variability on time scales $\Delta t \sim \ll 1\,\mathrm{min}$, suggests a very small emission region of size $R \ll c\Delta t \sim 1.8 \times 10^{12}$ cm. As for blazars, the fast flux variability and enormous brightness of GRBs implies a lower limit on the velocity of the emitting plasma (the only way to avoid high optical depth to pair production). In the case of GRBs, the lower limits typically lie between 99.995 and 99.99995% of the speed of light (i.e., bulk Lorentz factors Γ of 100–1000). This velocity implies that clocks in the comoving frame go between 100 and 1000 times slower than in the observers frame. Relativistic aberration leads to an extremely narrow emission cone with a $\lesssim 1°$ opening angle. This makes GRBs the most extreme examples of relativistic jets known. Common traits of AGN and GRB jets and breakthroughs in the theoretical understanding of the jets from these two types of objects will be discussed in Chapter 10.

1.3
The Role of Simulations

As the physics of jets are governed by classical physics (the special and general theories of relativity and classical electrodynamics) and by well-understood components of quantum mechanics, one might think that it is straightforward to simulate the formation and propagation of jets and their electromagnetic emission. Quite the opposite is the case, and it is only quite recently that numerical simulations are becoming an increasingly useful tool to complement analytical modeling of jet processes. As an example, the interested reader may consult a seminal – and still very instructive – review article on the theory of AGN jets [32], which hardly mentions any simulation results, and in the few cases in which it does, it does so for demonstrative purposes.

A major difficulty of numerical calculations is the wide range of scales (spatial and temporal), which are relevant for the properties of jets. Jets form in the surroundings of supermassive black holes with a characteristic size of the Schwarzschild radius

$$r_{\mathrm{Sch}} = \frac{2G\,M_{\mathrm{BH}}}{c^2} = 3 \times 10^{13}\,\frac{M_{\mathrm{BH}}}{10^8\,M_\odot}\ \mathrm{cm}\ , \tag{1.1}$$

which is comparable to the diameter of Earth's orbit, and carry energy over distances of several 100 kpc (3.1×10^{23} cm) – often exceeding the size of the host galaxy. Simulating a jet all the way from its base and covering its propagation over its full length is already a formidable task, given that the simulations should be in 3D, as 1D and 2D simulations cannot capture the topology of true plasma flows. Another issue that complicates simulations is that the processes of jet formation, acceleration, and confinement depend on processes on much smaller scales. The viscosity of the accretion disk and the magnetic field in the accretion disk are thought to be generated by the magnetorotational instability on spatial scales $\ll R_{\mathrm{S}}$. The stability of the jet, the shocks in the jet, and the particle acceleration processes in the jet are ultimately governed by processes on the order of a gyroradius r_{g} of mildly relativistic electrons and/or protons with

$$r_{\mathrm{g}} = \frac{c p_\perp}{e B} \approx 3.3 \times 10^7\,\frac{c p_\perp}{10\,\mathrm{GeV}}\left(\frac{B}{1\,\mathrm{G}}\right)^{-1}\ \mathrm{cm}\ , \tag{1.2}$$

where $p_\perp$ is the momentum of the particle perpendicular to the magnetic field, and B is the magnetic field. The magnetic field is thought to be on the order of $B \sim 10^4$ G in the accretion disk of a $10^8\,M_\odot$ black hole accreting with the Eddington rate [33], and $B \sim 1$ G at the base of the jet where gamma-rays are emitted [34].

A full simulation of jets and their emission would start with a dark matter plus magnetohydrodynamics simulation of the interstellar and/or intracluster plasma based on a cosmological simulation, which grows primordial density perturbations into the environments of AGNs. Subsequently, the accretion and jet formation process would be simulated, best with a general relativistic magnetohydrodynamic simulation. Last but not least, one would simulate the jet flow including the formation of shocks, the acceleration of high-energy particles, the various emission processes of these high-energy particles, and the interaction of the jet with the ambient material.

Although no one has carried through such a comprehensive simulation, numerical studies have achieved substantial progress over the last 30 years by focusing on well-defined problems (see Chapters 4, 10, and 11 for detailed descriptions). As examples, we would like to highlight a few results:

- Early hydrodynamical jet simulations improved our understanding of the structure of radio galaxies (e.g., [35] and references therein).

- Magnetohydrodynamical simulations of differentially rotating accretion disks have led to rediscovery of the magnetorotational instability, which produces viscosity in accretion disks (e.g., [36–38]).
- General relativistic magnetohydrodynamical simulations include all ingredients which are deemed to be important for the process of jet formation: general relativity, hydrodynamics, and magnetic fields [39]. Simulations are now able to reproduce how highly relativistic jets may form and accelerate, and are beginning to validate earlier analytic models (e.g., [40–42]).
- Codes have been developed to simulate the acceleration of high-energy particles [43, 44] and their emission [45, 46]. The codes can be used to determine the properties of jets even though they do not contain jet formation, nor the formation of shocks in the jets.
- Recent particle-in-cell simulations are starting to be able to simulate astrophysical shocks and the acceleration of particles in these shocks [47, 48].

Although in many cases, simulations reproduce observed characteristics, there may be fundamental aspects of real jets which are not included in the simulations. Conceptually, one might imagine that it would be possible to compare jets dominated by Poynting flux, protons, and pairs. We could then perform a test of each by attempting to bend the jets with an external force provided by the "wind" of a thermal plasma such as occurs for tailed radio galaxies in clusters of galaxies. As the growth of computing capabilities has followed Moore's law for the last half century (i.e., doubled approximately every two years) and is expected to continue in this way for quite some time to come, we can expect an interesting decade in which jet simulations will make enormous progress and will enable comparisons of simulated and observed characteristics, and of simulated and analytic results.

1.4 Jet Composition

By the term "jet composition" we mean "What is the means of transporting energy over vast distances?" We are fairly confident that we know the essential ingredients of the emitting volumes we call "knots" and "hot spots": a relativistic plasma consisting of at least a magnetic field (average value $\geq$ 1 μG), a rather wide (in energy) distribution of relativistic electrons (and/or positrons), and photons of the CMB and of other sources more particular to the local environment. A relatively straightforward argument [49] convinces us that the particles responsible for the electromagnetic radiation observed cannot be the means of transporting energy: electrons with $\gamma \geq 2000$ would lose their energy long before they reached the end of many long jets. Thus knots and hot spots should be viewed as products of the jet: sites where jet energy is transferred to the radiating plasma.

1.4.1 Options

The standard list of possibilities for jet composition is quite short. It basically consists of cold (thermal) or hot (relativistic) protons, cold electrons/positrons, and Poynting flux. Occasionally some other transporter has been suggested such as neutrons or low-frequency EM radiation, but these have not been embraced by the community, primarily because of difficulties associated with the genesis of the jet, and because of problems of how to deflect and bend jets (both of which have been observed in several jets).

1.4.2 Constraints

Most of the published works on jet composition are based on attempts to find evidence for the particle content: either pairs or normal plasma. The general approach is to seek an estimate of the total power requirements of the jet, and then come up with some estimate of how many electrons are in the jet (e.g., [50, 51]). If the energy transport relies on pairs, there have to be more electrons (and positrons) than if most of the energy is carried by protons. Sikora and Madejski [52] argue that pairs outnumber protons, but protons are the chief energy carrier.

Attempts to estimate the total number of electrons are fraught with uncertainty. As well as a blind faith that there are no spectral breaks at low energies, it is usually assumed that a steep power law describes the electron distribution, which is arguably the case for emitting regions, but not necessarily for the transport mechanism. Since a steep power law is assumed, estimates of the total number of electrons are extremely sensitive to the low-energy cutoff of the power law (γ_{min}, see for example [53]).

Various constraints from synchrotron theory have been invoked, including using the rotation measure to study parsec-scale jets with VLBI data. Wardle *et al*. [54] argued that on the parsec scale, the jets being studied had to consist of e^-, e^+ pairs: a pair plasma does not produce Faraday rotation.

Reynolds [55, 56] and others (e.g., [50, 51]) consider the effects of synchrotron self-absorption (SSA) in order to get an estimate of the magnetic field strength. However, it is notoriously difficult to find convincing values for the peak flux density and peak frequency of an absorbed component.

Sikora *et al*. [57] use various arguments to suggest that while jets are initially dominated by Poynting flux, they quickly become particle-dominated with protons as the primary transporter of energy.

In spite of the cunning arguments employed, we consider the question of jet content to be undecided.

1.5
Some Things (We Think) We Know, and Some (We Know) We Don't

We end this introductory chapter with a brief compilation of knowns and unknowns about jets. Knowns include:

- The jet phenomenon bridges many orders of magnitude in size: jets originate on subparsec scales and can propagate over many 100 kpc.
- Black holes are extreme powerhouses. While stars generate (or liberate) energy through nuclear fusion of lighter elements into heavier elements, mass-accreting black holes convert potential energy of interstellar matter into electromagnetic radiation and into jet energy. The jets carry away a substantial fraction of the accretion energy.
- The jet emissions we observe come from relativistic electrons.
- Hot (e.g., $\gamma > 2000$) electrons/positrons cannot be the agent of energy transport over huge distances.
- The polarized radio and optical jet emissions are synchrotron emission.
- The emitting plasmas of most/all jets are moving relativistically.
- Black holes are not only passive sinks of matter at the centers of galaxies and galaxy clusters. Their radiation and their jets have an impact on their host through heating and stirring of the interstellar and intracluster gas.

However, although theoretical concepts have evolved substantially over the last decades, the most important mechanisms concerning AGN accretion, jet formation, jet acceleration and collimation, and the various emissions from AGN jets are still the subject of a lively debate. Relevant questions include:

- How does black hole accretion work and how are jets launched?
- Which effects regulate the activity of AGNs and turn jets on and off?
- What mechanisms cause the spectacular flares of electromagnetic radiations from blazars?
- What is the composition of the "fluid" responsible for the energy transport at different distances from the supermassive black holes?
- What maintains the collimation of jets?
- What is the emission process for the spatially resolved X-rays from high-power sources such as radio quasars?
- How do jets accelerate particles to TeV energies?
- Are jets the sources of ultra-high-energy cosmic rays?

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