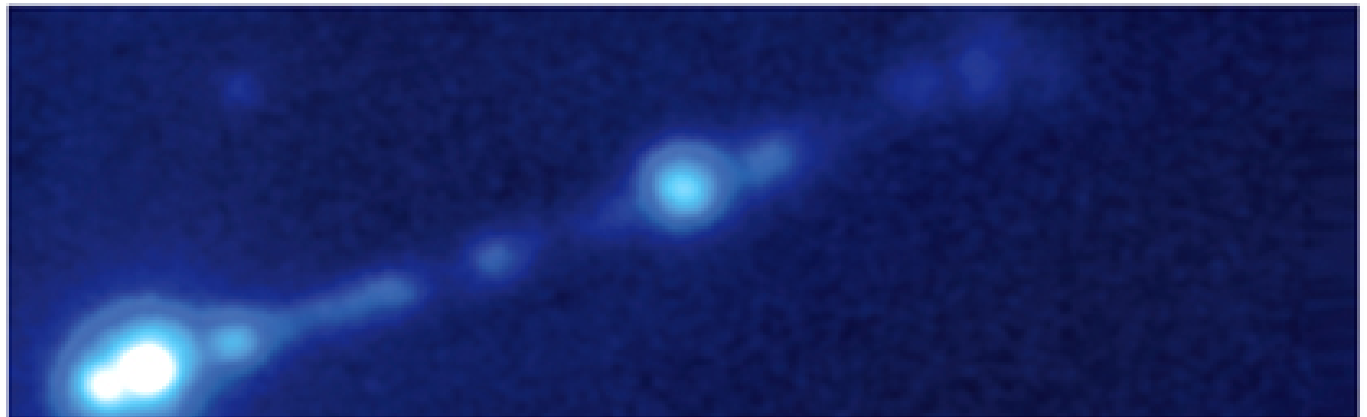
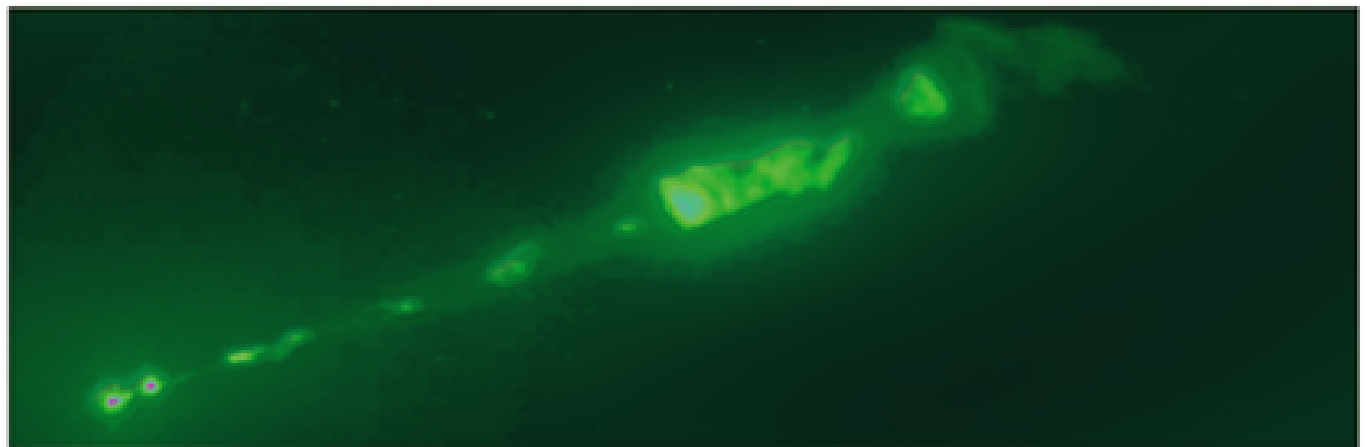
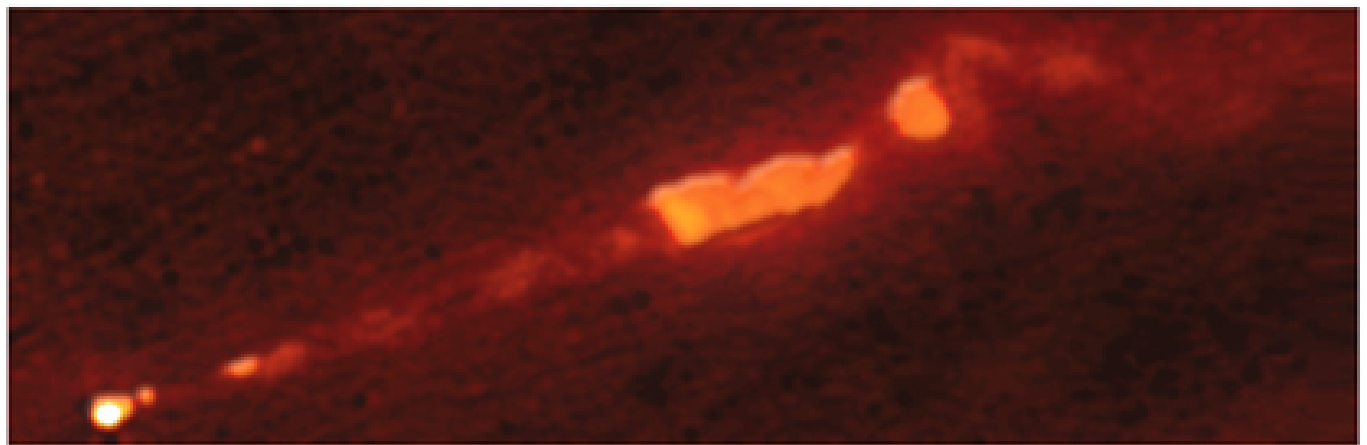


Edited by M. Boettcher, D. E. Harris,  
and H. Krawczynski

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# Relativistic Jets from Active Galactic Nuclei



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and Henric Krawczynski*



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# ***Preface***

The idea of writing a text book on extragalactic jets was initially beset by many doubts. Why produce a book on a subject that is only poorly understood at best? Most text books are the result of several years teaching a course on a relatively stable field of endeavor, but our understanding of jets is still evolving rapidly. Furthermore, the subject matter is very broad, ranging from cutting edge simulations, to relativistic MHD, and of course observations at the limits of our best instruments. We asked ourselves, is it worth our time to pursue this project? Yet in the end, we cast aside these doubts and convened a group of experts who each agreed to contribute a chapter. The reader of this book will see that although we do not know with certainty what jets are made of and how they are launched, accelerated and collimated, there is a vast body of observational evidence which has already been confronted with a wide range of theoretical models. Thus, although the theory of jets is beset with uncertainties, it is highly constrained at the same time. This book gives an overview of a mature and rich field in which key observational and theoretical breakthroughs as well as paradigm shifts can happen at any time.

The book is intended to be used by graduate students, teachers, and researchers who are interested in active galactic nuclei (AGN) and their relativistic outflows. The introductory chapters covering aspects of special relativity and radiation processes may be of interest to a broader audience, e.g., graduate students working in the fields of radio astronomy or high-energy astrophysics. Some of the more advanced chapters of this book will also be of interest to researchers in the field, as they give up-to-date reviews of the rapidly evolving subject matter.

We decided to limit the book to relativistic jets from AGN. Although jets from microquasars may share much the same physics as our AGN jets, we felt that we could not treat the

subject matter of galactic binaries adequately given the constraints of the project. We also decided not to deal with jets from gamma-ray bursts mainly because we felt that while again the underlying physics may be similar, there are so few observables available that jet models for GRB are difficult to disprove by observation. Stellar jets are another subject we decided to exclude since they are not believed to be relativistic.

We thank the staff at Wiley for their patience and assistance. We are very grateful to E. Mandel (SAO) who kindly wrote the scripts to facilitate construction of the index.

September 2011

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*D. E. Harris*  
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# ***Glossary and Acronyms***

AMR	Adaptive Mesh Refinement
AMRVAC	Adaptive Mesh Refinement Versatile Advection Code
ATCA	Australian Telescope Compact Array
BLR	Broad-Line Region (as seen in AGN spectra)
BeppoSAX	A small X-ray satellite launched in 1996
Big blue bump (BBB)	A spectral feature of some AGN thought to arise from the accretion disk
CJF	Caltech-Jodrell Bank Flat Spectrum VLBI Survey
CSO	Compact Symmetric Object (describing a small radio source)
CSS	Compact Steep Spectrum (describing a small radio source)
Chandra	One of NASA's "Great Observatories"; for X-ray imaging and spectroscopy
EBL	Extragalactic Background Light
EVLA	Extended Very Large Array. The upgraded workhorse of radio astronomy in New Mexico
Fermi	A NASA mission for MeV and GeV observations, a.k.a. FGST: Fermi Gamma-Ray Space Telescope
FIDO	Fiducial observer
FSRQ	Flat-Spectrum Radio Quasar
Faraday rotation	The rotation of the angle of the linear polarization during propagation through a magnetized plasma
GEMS	Gravity and Extreme Magnetism SMEX
GMVA	Global Millimeter VLBI Array
GPS	Gigahertz-peaked spectrum. A radio source with peak flux density in the GHz range
GRB	Gamma-ray burst
HALCA	Highly Advanced Laboratory for Communications and Astronomy
HBL	High-frequency (peaked) BL Lac object
H.E.S.S.	High-Energy Spectroscopic System. A GeV/TeV gamma-ray observatory in Namibia (a.k.a. HESS)
HETE II	High-Energy Transient Explorer II
HST	Hubble Space Telescope
HYMORS	Hybrid Morphology (Radio) Source. Usually one side is like FR I, the other FR II
High-Polarization Quasar	Quasar with a high degree of optical polarization (HPQ)
IGM	Intergalactic medium
ISM	Interstellar medium

IXO	International X-ray Observatory
LDQ	Lobe-Dominated Quasar (radio morphology)
LOFAR	Low-Frequency Array for Radio Astronomy
MAGIC	A GeV/TeV gamma-ray observatory in the Canary Islands
MERLIN	Multielement Radio-Linked Interferometer
MOJAVE	Monitoring of Jets of AGN with VLBI Experiments
NLR	Narrow-line region
OSSE	Oriented Scintillation Spectrometer Experiment
OVV	Optically Violent Variable
PARAMESH	Parallel Adaptive Mesh Refinement
Poynting Flux	Energy flux carried by electromagnetic fields, $S = (\frac{1}{\mu_0})E \times B$ (in SI units)
RHD	Relativistic hydrodynamics
RMHD	Relativistic magnetohydrodynamics
RRFID	Radio Reference Frame Image Database
SED	Spectral energy distribution
SKA	Square Kilometer Array
SSA	Synchrotron self-absorption
SSC	Synchrotron self-Compton (emission)
TANAMI	Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry
UHECR	Ultra-high-energy cosmic ray
VCS1	VLBA Calibrator Survey No. 1
VERITAS	Very Energetic Radiation Imaging Telescope Array System. A GeV/TeV gamma-ray observatory in Arizona
VIPS	VLBA Imaging and Polarimetry Survey
VLA	Very Large Array. Twenty-seven element radio interferometer in New Mexico
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VSOP	VLBI Space Observatory Program
ZAMO	Zero Angular Momentum Observer

# ***Part One***

## ***Introduction***

# ***Chapter 1***

## ***Introduction and Historical Perspective***

***Markus Böttcher, Daniel E. Harris, and Henric Krawczynski***

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.

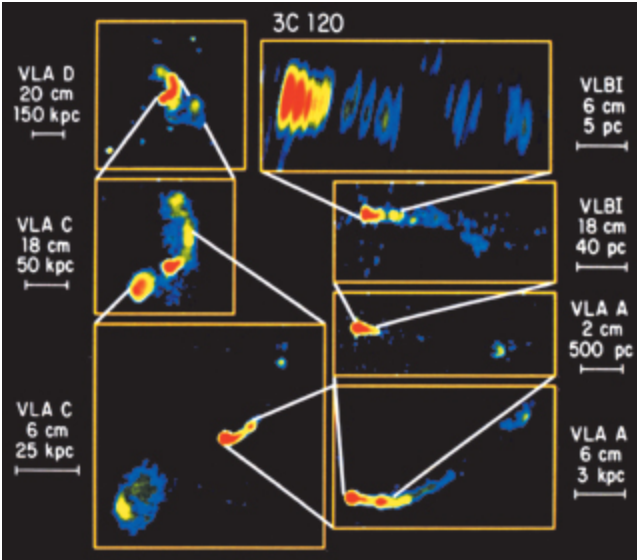
### **1.1 A Brief History of Jets**

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.  $20^\circ$ , 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  $r = 10^{-4} M_{\text{BH}} / 10^9 M_{\odot}$  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 range of scales covering a factor of  $10^{10}$ ! Some sense of this vast range of scales is provided by [Figure 1.1](#).

**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.



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 $\gamma$ -Rays**

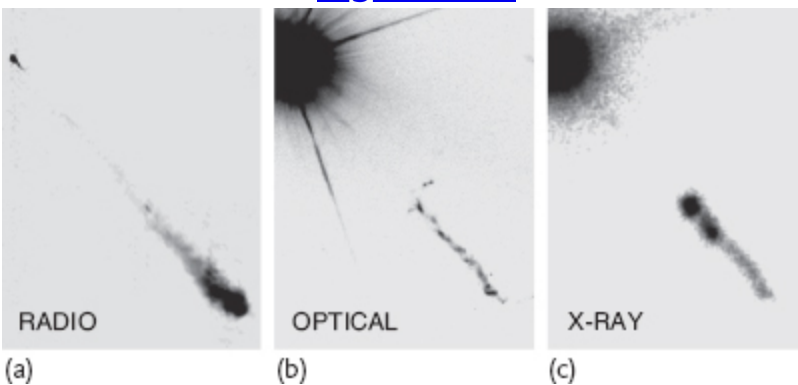
At the higher frequencies, the synchrotron  $E^2$  half-lives are on the order of several years in typical fields of 0.1–1 mG. Since we have optical polarization from many jets and, at least in the case of knot HST-1 in the M 87 jet where we have strong variability at all wavelengths, we are confident 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.