19. D. E. Winget *et al.*, *Astrophys. J.* **315**, L77 (1987); I. Iben, Jr., and G. Laughlin, *ibid.* **341**, 312 (1989).
20. R. B. Larson, in *Dynamics and Interactions of Galaxies*, R. Wielen, Ed. (Springer-Verlag, Berlin, 1990), p. 48.
21. ______, *Mon. Not. R. Astron. Soc.* **176**, 31 (1976).
22. D. J. Stevenson, *J. Phys. Coll.* **41**, C2-61 (1980)
23. S. Ichimaru, H. Iyetomi, S. Ogata, *Astrophys. J.* **334**, L17 (1988); J. L. Barrat, J. P. Hansen, R. Mochkovitch, *Astron. Astrophys.* **199**, L15 (1988).
24. J. Isern, R. Mochkovitch, E. Garcia-Berro, M. Hernanz, *Astron. Astrophys.* **241**, L29 (1991).
25. K. S. Holian, Ed., *T-4 Handbook of Material Properties Data Bases* (Publication LA-10160-MS, UC-34, Los Alamos National Laboratory, Los Alamos, NM, 1984); P. C. Souers, *Hydrogen Properties for Fusion Energy* (Univ. of California Press, Berkeley, 1986).
26. D. Saumon, thesis, University of Rochester, Rochester, NY (1990); ______ and G. Chabrier, *Phys. Rev. Lett.* **62**, 2397 (1989).
27. S. Ichimaru, personal communication.
28. D. Ceperly and B. Alder, *Science* **231**, 555 (1986).
29. M. Ross, F. H. Ree, D. A. Young, *J. Chem. Phys.* **79**, 1487 (1983).
30. W.-D. Kraeft, D. Kremp, W. Ebeling, G. Röpke, *Quantum Statistics of Charged Particle Systems* (Plenum, New York, 1986).
31. M. van Thiel *et al.*, *Phys. Earth Planet. Inter.* **9**, 57 (1974); W. J. Nellis, A. C. Mitchell, M. van Thiel, G. J. Devine, R. J. Trainor, *J. Chem. Phys.* **79**, 1480 (1983).
32. F. V. Grigor'ev, S. B. Kormer, O. L. Mikhailova, A. P. Tolochko, V. D. Urlin, *JETP Lett.* **16**, 201 (1972).
33. R. J. Hemley and H. K. Mao, *Phys. Rev. Lett.* **61**, 857 (1988); H. K. Mao and R. J. Hemley, *Science* **244**, 1462 (1989); H. E. Lorenzana, I. F. Silvera, K. A. Goettel, *Phys. Rev. Lett.* **64**, 1939 (1990).
34. A. N. Cox and J. N. Stewart, *Astrophys. J. Suppl.* **11**, 22 (1965); *ibid.* **19**, 243 (1970); *ibid.*, p. 261.
35. C. A. Iglesias, F. J. Rogers, B. G. Wilson, *Astrophys. J.* **322**, L45 (1987); *ibid.* **360**, 221 (1990).
36. D. R. Alexander, *Astrophys. J. Suppl.* **29**, 363 (1975); ______, H. R. Johnson, R. L. Rypma, *Astrophys. J.* **272**, 773 (1983).
37. J. I. Lunine, W. B. Hubbard, A. Burrows, Y.-P. Wang, K. Garlow, *Astrophys. J.* **338**, 314 (1989).
38. P. Lenzuni, D. F. Chernoff, E. E. Salpeter, *ibid.*, in press; A. Borysow and L. Frommhold, *ibid.* **348**, L41 (1990).
39. W. Däppen, D. Mihalas, D. Hummer, B. Mihalas, *ibid.* **332**, 261 (1988); A. K. Pradhan, in *Atomic Processes in Plasmas*, A. Hauer, Ed. (American Institute of Physics, New York, 1988), p. 59.
40. F. D'Antona and I. Mazzitelli, *Annu. Rev. Astron. Astrophys.* **28**, 139 (1990).
41. W. B. Hubbard and M. Lampe, *Astrophys. J. Suppl.* **18**, 297 (1969).
42. E. Flowers and N. Itoh, *Astrophys. J.* **206**, 218 (1976); N. Itoh, S. Mitake, H. Iyetomi, S. Ichimaru, *ibid.* **273**, 774 (1983); D. G. Yakovlev, *Sov. Astron.* **31**, 347 (1987); S. Mitake, S. Ichimaru, N. Itoh, *Astrophys. J.* **277**, 375 (1984); R. Nandkumar and C. J. Pethick, *Mon. Not. R. Astron. Soc.* **209**, 511 (1984); N. Itoh, Y. Kohyama, N. Matsumoto, M. Seki, *Astrophys. J.* **285**, 758 (1984).
43. E. H. Gudmundsson, thesis, University of Copenhagen, Copenhagen, Denmark (1981).
44. Y. Sang and G. Chanmugam, *Astrophys. J.* **323**, L61 (1987); C. E. Wendell, thesis, University of Rochester, Rochester, NY (1990).
45. E. E. Salpeter, *Aust. J. Phys.* **7**, 353 (1954).
46. A. G. W. Cameron, *Astrophys. J.* **130**, 916 (1959); E. E. Salpeter and H. M. Van Horn, *ibid.* **155**, 183 (1969); S. Schramm and S. E. Koonin, *ibid.* **365**, 296 (1990).
47. M. Fleischmann, S. Pons, M. Hawkins, *J. Electroanal. Chem.* **261**, 301 (1989).
48. H. E. DeWitt, H. C. Graboske, M. S. Cooper, *Astrophys. J.* **181**, 439 (1973).
49. A. Alastuey and B. Jancovici, *ibid.* **226**, 1034 (1978); C. Carraro, A. Schäfer, S. E. Koonin, *ibid.* **331**, 565 (1988); S. Ogata, H. Iyetomi, S. Ichimaru, *ibid.*, in press; S. Ichimaru and S. Ogata, *ibid.*, in press.
50. N. Itoh, T. Adachi, M. Nakagawa, Y. Kohyama, H. Munakata, *ibid.* **339**, 354 (1989); erratum, *ibid.* **360**, 741 (1990).
51. D. Saumon, personal communication.
52. D. E. Winget, thesis, University of Rochester, Rochester, NY (1981).
53. H. M. Van Horn, *Mitt. Astron. Gesellschaft.* **67**, 63 (1987).
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Astrophysical Jets

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Astrophysical jets are linear structures associated with stars and galaxies which span about seven orders of magnitude in size; the largest jets emanating from galaxies are about 100 times the size of our galaxy and are the largest single objects in the universe. Jets associated with stars are composed of ionized gas moving away from the star with velocities of a few hundred kilometers per second. Extragalactic jets are composed of relativistic particles, magnetic field, and probably additional amounts of cooler ionized plasma either originally ejected in the jet or entrained by it out of the surrounding gaseous medium. The initial outflow velocity for extragalactic jets may be relativistic, and average outflow speeds of several thousand kilometers per second are likely. The energy flux carried by extragalactic jets may be in excess of 10^{46} ergs per second, depending upon the nature of the jet. A definition of jet properties, deduced from their interaction with the ambient medium, can place essential constraints on models for the central power source in the parent galaxy or quasi-stellar object where they originate.

ASTROPHYSICAL JETS ARE ELONGATED AND WELL COLLIMATED structures associated with a variety of astronomical objects that range from single stars to entire galaxies. As the name implies, they are believed to be composed of streams of high velocity gas flowing out from the associated astronomical object, although in some of the most important classes of jet no outflow velocity has been directly measured. Ejection of gas from an astronomical object is a common phenomenon; young stars lose a large amount of their mass in this way, and our own sun produces a solar wind that interacts in a significant way with Earth's magnetosphere. However, these flows are largely spherically symmetric, often with imbedded filamentary structure. Astrophysical jets are unlike these in that they are truly jet-like and not merely a feature of some more general outflow phenomenon. One of the unique aspects of astrophysical jets is that they cover an astonishing range in size. The jets associated with young stars are typically 10^{17} cm in length, while the jets associated with some giant galaxies have an overall extent in excess of 10^{24} cm. These latter objects are the largest single continuous structures found in the universe. Thus the jet phenomenon is seen on scales that cover seven orders of magnitude, yet there is evidence that the important physical processes are much the same in all of them.

Astrophysical jets play a key role in our efforts to understand some

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of the most basic and the most spectacular phenomena observed in astronomy. The nature of the interaction of a jet with its environment can provide valuable information about the jet itself, such as its velocity, energy density, magnetic field content if any, and so forth. Conversely, if the jet parameters are well understood, this interaction can provide information about the nature of the ambient medium into which the jet is propagating. When the major dynamical characteristics of a jet have been determined, important boundary conditions can then be placed on models that attempt to describe the origin and collimation of the jet, and it is this aspect that most strongly motivates the study of astrophysical jets. For example, extragalactic jets not only provide the largest coherent structures in the universe, they are also conduits for the transport of enormous amounts of energy in a very specialized form. Up to 10^{60} ergs of energy in the form of relativistic electrons and magnetic field may be transported by such jets. This is more energy than that produced by all the stars in our own galaxy over a period of 100 million years. Objects of this nature are clearly of interest in themselves, but an associated and perhaps more important problem is the nature of the central "engine" lying deep in the center of a galaxy or quasi-stellar object (QSO) which provides such prodigious amounts of energy in such a special form. Understanding the nature of these jets—their geometry, content, velocity, viscosity, and so on—provides limits on the total energy output required by the central mechanism, information about the physical conditions in these central regions, insight into the formation and history of the parent galaxy or QSO, and, most recently, possible constraints on current cosmological models of the universe itself.

Overview of Jet Properties

Stellar jets. Collimated outflows are often seen in association with young stellar objects. The frequency of occurrence of these flows is not well established; general mass outflow occurs in the early stages of stellar evolution, and it may be that a significant fraction of these show some degree of collimation. These flows are often bipolar, and the poorly collimated examples may be produced by a thick disk of protostellar material intercepting a generally spherically symmetric outflow from a very young star (*1*). However, this mechanism is unlikely to provide the necessary collimation for the narrower jet-like structures discussed here. Figure 1 shows a striking example of a jet associated with a young star; the high degree of collimation is clearly evident. Stellar jets such as this are characterized by outflow velocities of a few hundred kilometers per second, which is highly supersonic relative to the ambient medium, and by number densities which generally lie in the range of 10^2 to 10^3 cm^{-3} (*1*). The jet shown in Fig. 1 is thought to become invisible over much of its length because it has cooled and no longer radiates (*2*). The feature at the bottom of the figure is very suggestive of the bow shock that would result when a supersonic jet impinges upon the ambient medium, and this feature presumably marks the terminus of the jet as it makes its way through the interstellar medium. The presence of atomic emission line features from hydrogen, oxygen, nitrogen, and sulfur in stellar jets allows direct measurement of the jet velocity component along the line of sight as well as a determination of the density in the jet. These important dynamical parameters cannot be directly measured in extragalactic jets and thus the stellar jets provide important information about the interaction of jets with their ambient medium. It will be seen that an understanding of this interaction is a necessary first step in understanding the origins of jets in other galaxies. A detailed understanding of the origin and collimation of narrow stellar jets is not yet available. Mass loss from very young stars is probably driven by radiation pressure from the star itself, but very narrow collimation is difficult if not impossible to achieve by a gravitationally maintained accretion disk of dust and gas surrounding the star, though the process may be mediated by magnetic fields (*3*). The knot-like structure along the jet shown in Fig. 1 is a common phenomenon in stellar jets and may indicate an intermittent nature of the outflow. A clear understanding of the collimation mechanism will add significantly to our understanding of the early stages of stellar evolution and of the star formation process itself. It is known that collimation is achieved very close to the stellar surface, but additional observations and theoretical modeling are required for a complete understanding of the phenomenon.

Extragalactic jets. Stellar jets are observed at optical wavelengths from recombination radiation emitted by the hot ionized gas in the jet. Radiation from extragalactic jets arises instead from synchrotron radiation produced by an ensemble of relativistic particles embedded in a magnetic field. The spectrum of this radiation is fit very well by a power law, $I(\upsilon) \propto \upsilon^{-\alpha}$, where υ is the frequency of the radiation, and this in turn can be produced by an ensemble of relativistic electrons with an energy distribution given by $N(E)dE = CE^{-\Gamma}dE$, where $\Gamma = 2\alpha + 1$ (*4*). In general, the value of α varies somewhat along the jet and from jet to jet, but it usually lies in the range 0.2 to 1.0, with the most common value being around 0.7. Almost all extragalactic jets are observed at radio frequencies and not at optical wavelengths. This occurs because the timescale for energy loss due to synchrotron radiation at a given frequency υ is proportional to $B^{-3/2}\upsilon^{-1/2}$ where B is the magnetic field mixed with the electrons.

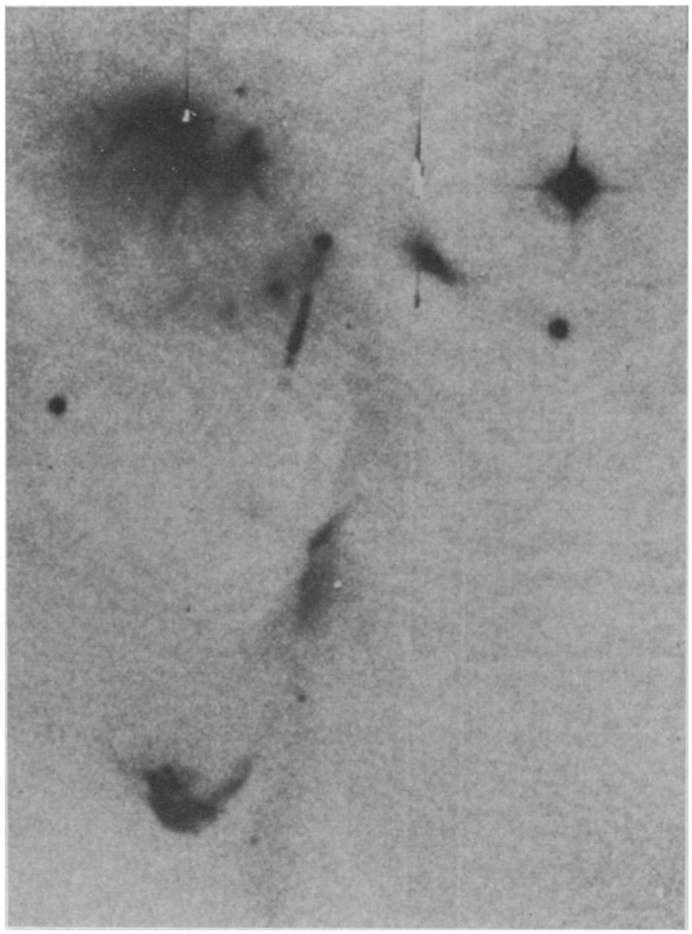

Fig. 1. An example of a well-collimated jet propagating in the interstellar medium and which originates at a young star. The object is known as HH-34, and the possible bow shock is at the bottom of the figure. [Reprinted from (*2*), with permission from the American Astronomical Society]

Hence the lifetime for radiation at high frequency is very short, typically 10^5 years at optical wavelengths.

The morphology of extragalactic jets varies considerably, as does the scale upon which they occur. Some representative examples are shown in Figs. 2 to 5. Figure 2 shows the jet emanating from the center of the nearby elliptical galaxy M87. This is one of the few jets that emit at optical wavelengths as well as at radio frequencies. The effects of the frequency dependent radiative lifetime described above can be seen in comparing Fig. 2, a and b; the extent of the emission at radio wavelengths is considerably greater than that in the optical region. The M87 jet clearly arises in the very nucleus of the galaxy, and this nuclear origin appears to be the case for all jets observed to date. Figure 3 is a series of radio maps of the jet arising from the center of the galaxy NGC 6251, and it shows the extremely high degree of collimation maintained by the jet from its origin out to a distance of 172 kpc, or 5.2×10^{23} cm (1 parsec = 3×10^{18} cm or 3.3 light-years). The existence of linear structure over such large distances is an essential feature that must be explained by any successful model of these jets. Figure 3 also displays two other aspects common to these extragalactic radio sources. The first is the presence of the large double-lobed structure, which in this case exceeds a million parsecs, or 3×10^{24} cm, making this radio source one of the largest objects in the universe. The overall extent of this object is almost 100 times the size of our own galaxy. The second is the presence of two oppositely directed jets emanating from the nucleus, with one jet clearly predominant. In many objects only one jet is seen, yet the large-scale double-lobed structure remains. This "one sidedness" in jets is an important issue in understanding jet dynamics. For example, one of the most important questions about

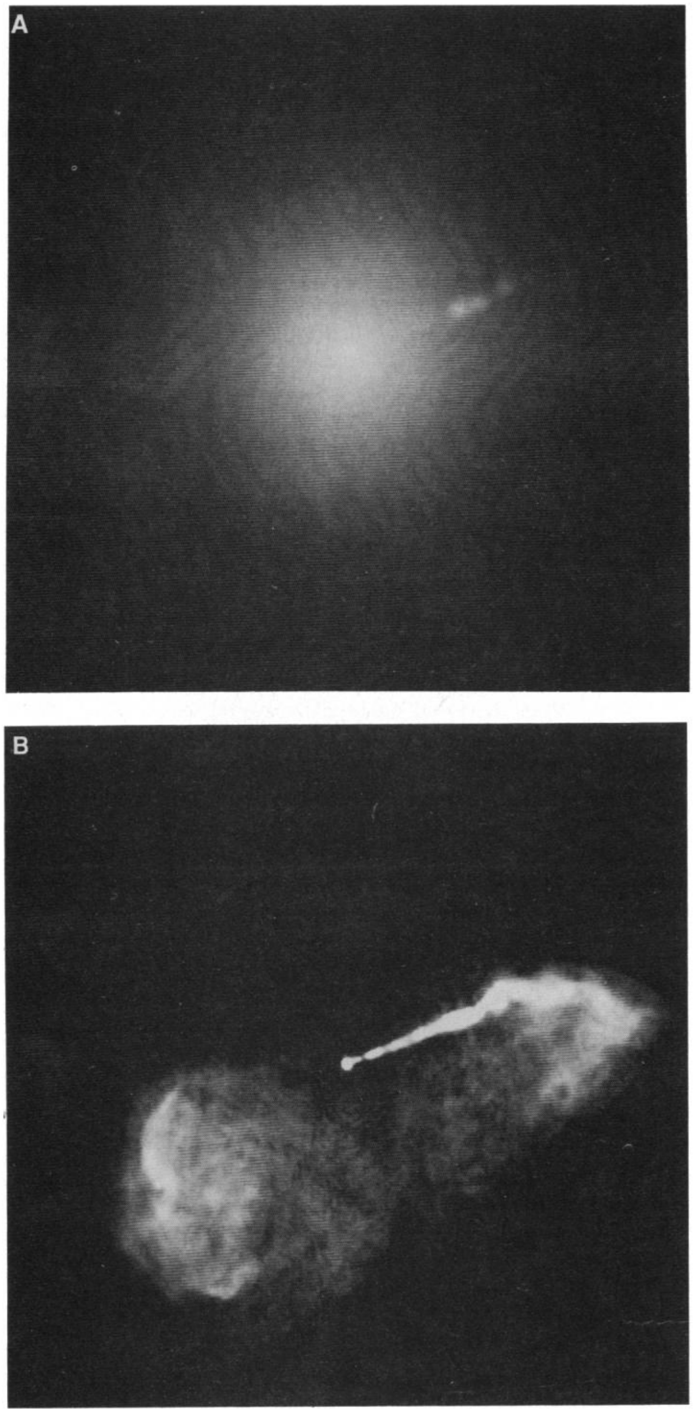

Fig. 2. Extragalactic jet emanating from the center of the elliptical galaxy M87. (**A**) The rare optical emission of this jet at 8000 Å; (**B**) shows the emission at a radio wavelength of 2 cm. The projected length of the jet is about 2 kpc, and the two figures are on the same scale. [Figures kindly provided by Dr. John Biretta]

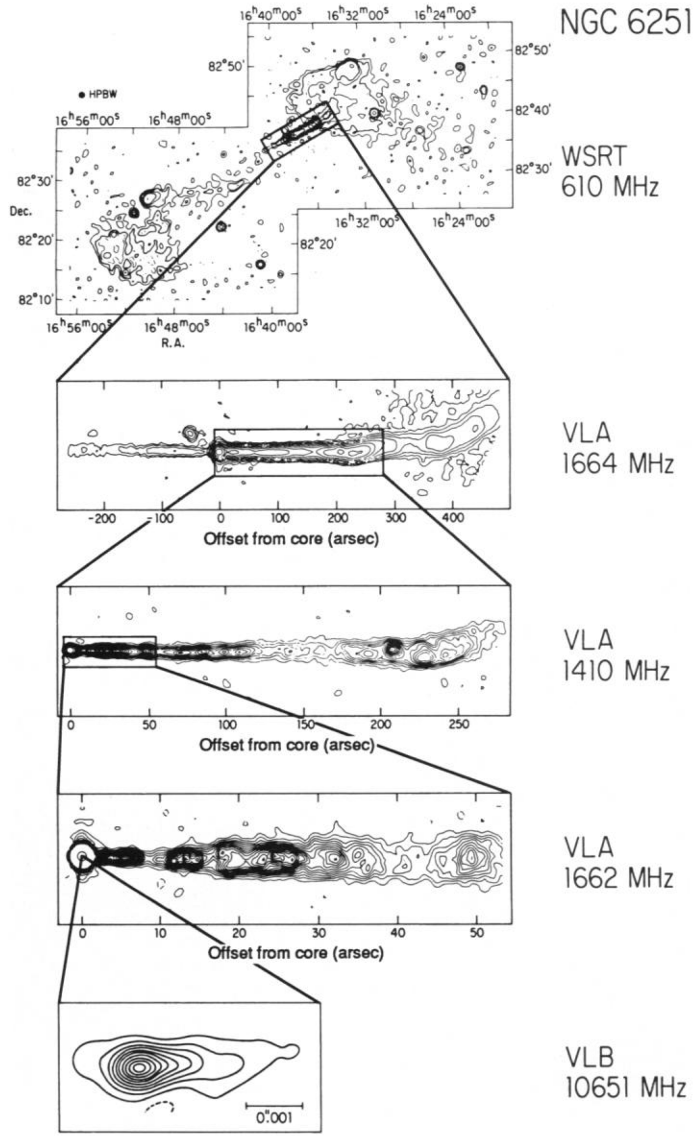

Fig. 3. Jet in the galaxy NGC 6251 at various scales of resolution. [Reprinted from (*5*), with permission from Annual Reviews, Inc.]

one-sided jets revolves around the origin of this asymmetry. It is possible that the outflow from the nucleus is intrinsically one sided, although the presence of the double lobes implies that this one-sided outflow must somehow alternate from side to side, and this is a condition that places serious constraints on dynamical models of the origin of the jet. It is also possible that two symmetric jets exist but that one has been obscured by intervening material or that the other appears much brighter because it is directed toward the observer and has its intensity enhanced by the Doppler effect. These questions will be discussed in more detail later. Other examples and statistics on "sidedness" are given in the review by Bridle and Perley (*5*). The lobes themselves are made of relativistic electrons, protons, magnetic field, and possibly a largely undetermined amount of ionized but cooler, nonrelativistic plasma. The ambient medium surrounding the lobes is a very tenuous but ionized plasma. In some cases this plasma is directly observed by x-ray bremsstrahlung, in other cases it is inferred from the radio source morphology as described below. The morphology shown in Fig. 3 strongly suggests that the two jets are flowing outward into the large double lobes, and this idea is supported by a simple argument based on the radiative lifetime of relativistic electrons in the lobes. Given the observed size of the radio source, and assuming that the two lobes were ejected from the nucleus, then for many large sources the synchrotron radiation would have died away before the electrons could have traveled to their present position, even if the ejection speed was maintained at essentially the speed of light. (This argument assumes a value for the magnetic field which minimizes the total energy required to create the radio-emitting plasma.) This difficulty is particularly acute for those few objects which show synchrotron emission at optical wavelengths, such as M87. Hence the radiating electrons need to be replenished or re-energized, and continuously outflowing jets from some central energy source, first proposed by Blandford and Rees (*6*), is an attractive idea and one which is supported by observations. Such jets are required to supply a minimum of 10^{42} to 10^{45} ergs s^{-1} to the extended radio source, and the implications of this requirement will be discussed below. It is important to note that the velocity of the large-scale jets is completely unknown, since there are no spectral features in the synchrotron radiation that would permit direct measurement of a velocity. This unfortunate uncertainty provides a major challenge in determining the possible range of jet velocities by indirect means, and it is the focus of considerable current effort.

Figure 4 shows a radio map of a classical double radio source, Cygnus A. Although this object was one of the first extended extragalactic radio sources discovered, it is only recently that technology has enabled production of the extremely high-resolution radio map shown here. In the figure it is possible to see the two faint, oppositely directed jets emanating from the center of the galaxy out to the ends of the lobes. Again, the data are suggestive of outflowing jets which can carry energy to the remote regions of the radio source. Figure 4 illustrates another feature which is being revealed in many extended radio sources by the latest high resolution images, namely the presence of filamentary structure which appears to fill the volume of the radio-emitting region. If this proves to be a common property of these objects, it has very important implications for the overall energy requirements and for the nature of the dynamical state of the interior of the radio source. Figure 5 is an example of a very large-scale jet structure occurring in a class of radio sources associated with galaxies located in clusters of galaxies. The overall extent of the radio emission is several megaparsecs, again

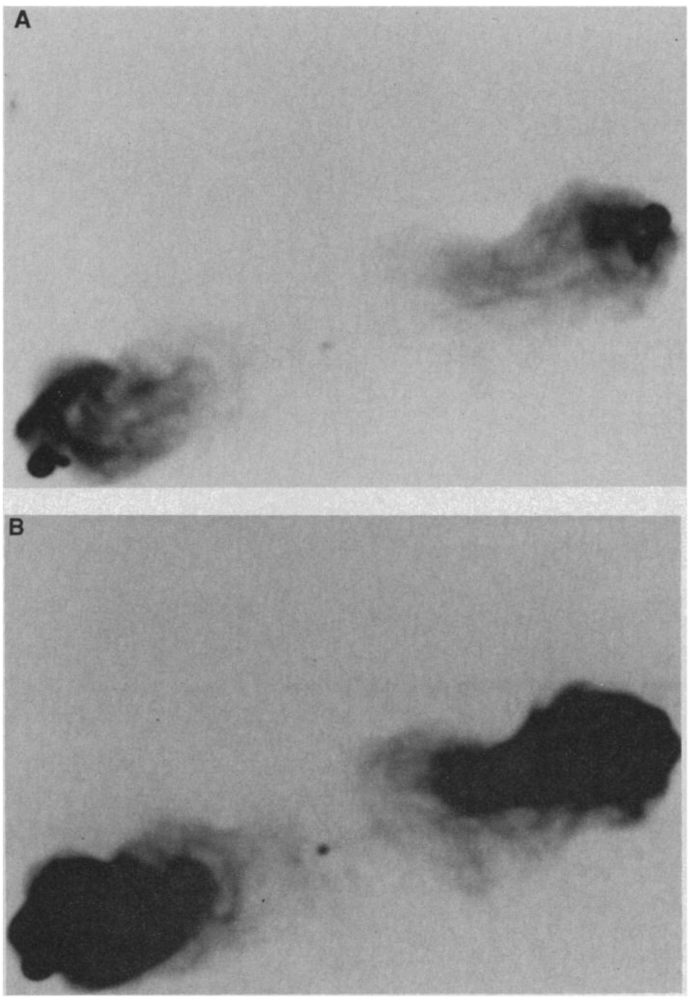

Fig. 4. (**A**) Radio "photograph" of the double-lobed radio source Cygnus A. The faint jets emanating from the nucleus can just be seen. (**B**) Same object, slightly more exposed. [Reprinted from (*26*), with permission from the American Astronomical Society]

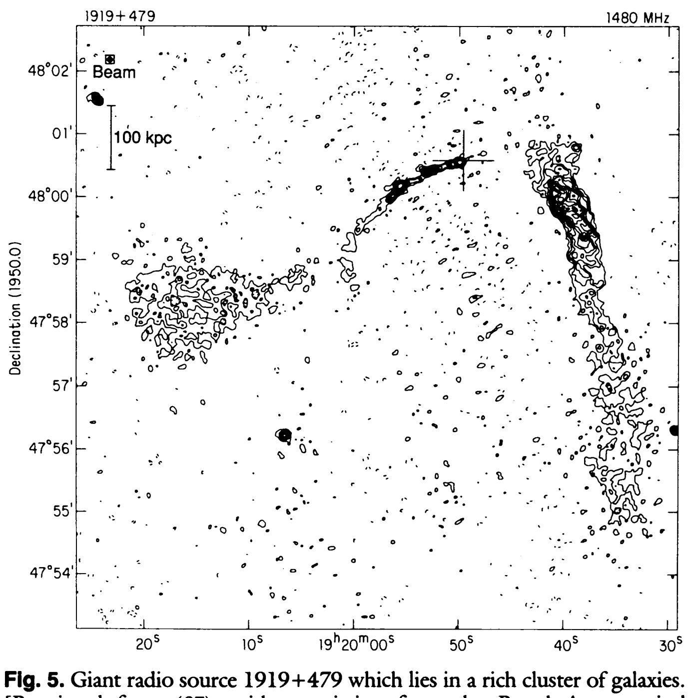

Fig. 5. Giant radio source 1919+479 which lies in a rich cluster of galaxies. [Reprinted from (*27*), with permission from the Royal Astronomical Society]

making it one of the largest objects in the universe. An important feature of this class of radio source is the bent morphology of the jets; understanding the origin of such bending will provide valuable constraints on the dynamics of the jets. Another example of the bending phenomenon is seen in Fig. 6, which is also representative of a class of radio galaxies which reside in rich clusters of galaxies. Here the bending is much more pronounced and much more symmetric and is clearly suggestive of a strong interaction with an ambient medium surrounding the jet.

A final example is shown in Fig. 7, which contains observations made at various wavelengths of the double-lobed radio galaxy 3C 368. This is an extremely distant galaxy, with a redshift of 1.13, and it is a member of a class of objects which has only very recently been discovered (*7, 8*), all of which are galaxies with double radio lobes, and all of which are extremely faint and which have very high redshifts. These objects are a new and significant probe of the early universe; at a redshift of 1.13, 3C 368 achieved its present state when the universe was less than 45% of its present age, and several of these galaxies have been found with redshifts in excess of 3, an epoch corresponding to less than one-fifth the age of the universe. Although the radio map of 3C 368 is very similar to many nearby double-lobed radio galaxies, the morphology at other wavelengths is completely unlike galaxies at the present epoch. In particular, the continuum, emission line and infrared images all show a strongly elongated morphology which is aligned with the radio source. Nearby radio galaxies show *no* correlation between their optical images and the geometry of the radio lobes (*9*). This difference is of clear cosmological significance and may provide insight into the process of galaxy formation. Narrow collimated jets have not yet been seen in these objects, but at their extreme distance jets of luminosity equal to those seen nearby would not be detected with current radio telescopes. Given the similarity of the large-scale radio structure to more nearby objects, there appears no reason not to assume that these most distant radio galaxies also contain well-collimated jets.

Critical Issues

Total energy. In the case of extragalactic jets, energy replenishment by the jets into the extended radio emitting regions must occur at a rate of 10^{42} to 10^{45} ergs s^{-1} in order to maintain the synchrotron radiation that is observed. This is an absolute minimum value in that it assumes all of the energy supplied is radiated away, and it provides a minimum energy requirement for the central source of power in the galaxy or QSO nucleus. The nature of the jet may make this energy requirement even larger. Replenishment of energy into the extended lobes can occur in two ways: either by direct resupply of "fresh" relativistic electrons which have been transported in a relatively lossless manner by the jet from the nucleus to the radio

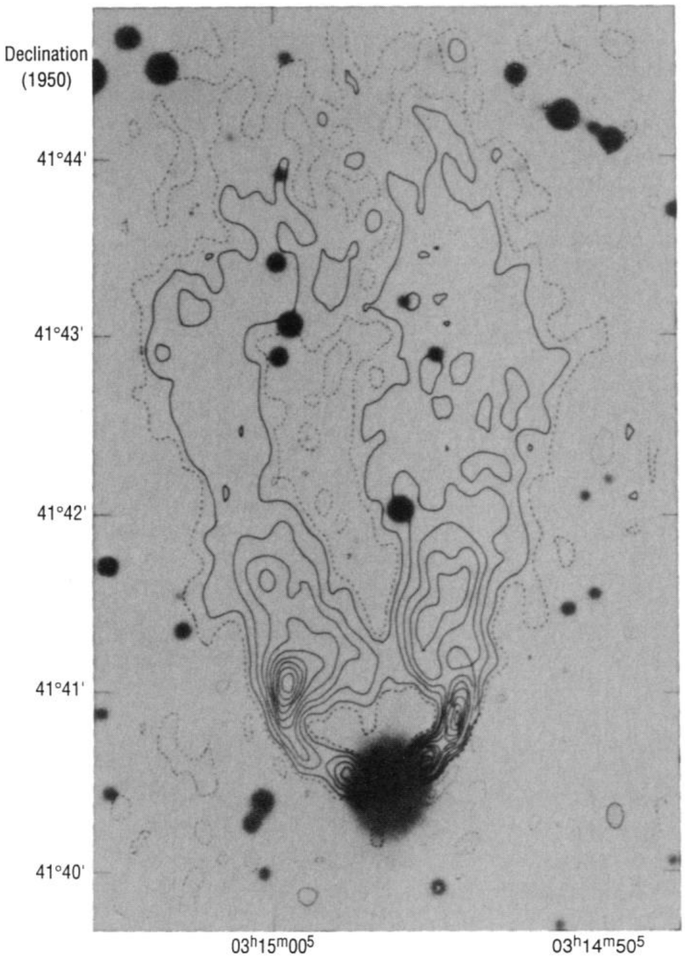

Fig. 6. Head-tail radio source emanating from the galaxy NGC 1265. This galaxy also resides in a rich cluster of galaxies. The radio contours are superposed on a photographic negative which shows the extent of the galaxy together with some foreground stars. [Reprinted from (*28*), with permission from Annual Reviews, Inc.]

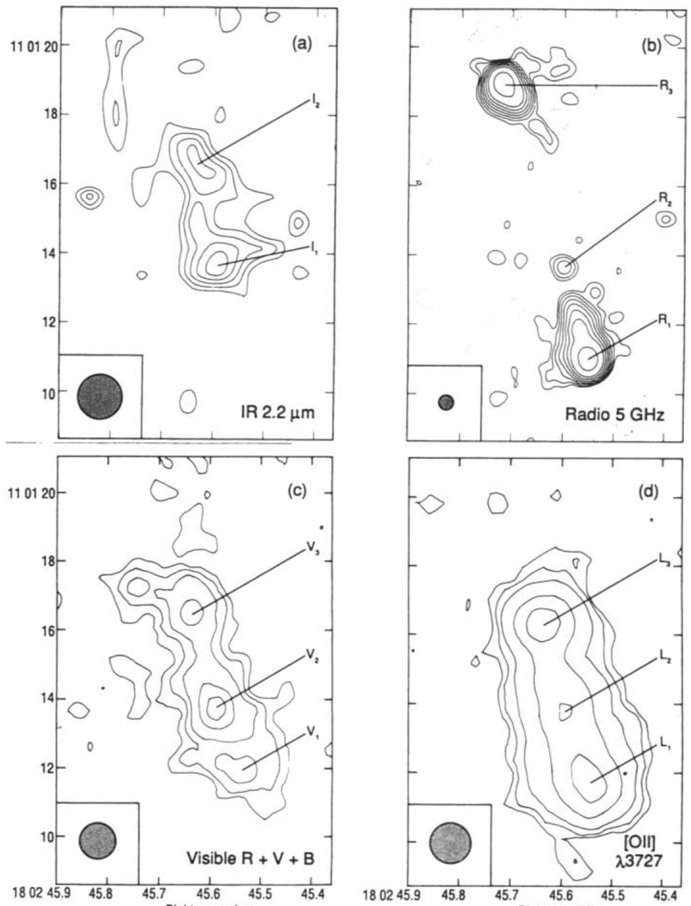

Fig. 7. Images of the high redshift radio galaxy 3C 368 at various wavelengths; infrared, radio, optical continuum, and the emission line of oxygen. The resolution element or "beam size" is shown in the lower left of each panel. [Reprinted from (*29*), with permission from the American Astronomical Society]

lobes, or by a supply of kinetic energy which can be used to stochastically reaccelerate the extant, energy-depleted electron population by mechanisms such as relativistic shocks.

Resupply by the first mechanism could be fairly efficient if the jet velocity is relativistic over much of its length and if the jet composition is "clean" in that it carries only relativistic electrons and their accompanying protons. As will be discussed below, it is unlikely that such jets can be both "clean" and relativistic. Slower jets, jets which lose a significant amount of energy, and jets which contain a large amount of nonrelativistic matter are all less efficient, and they thus increase the total energy requirement placed upon the central power source. Energy resupply by the second process is probably even less efficient, since the stochastic acceleration mechanisms likely to be present in the extended radio lobes have efficiencies of order 10% or less (*10*). Thus a determination of the composition of these jets, their velocities, and the nature of their interaction with the surrounding medium can have a profound effect on estimates of the amount of energy that must be supplied by the central power source, and this in turn constrains models that propose to explain the origin of these objects.

Composition. The composition of stellar jets is fairly well known, thanks to the presence of ionized hydrogen and heavier elements. Recombination radiation from these elements provides a measure of density and temperature as described above. The abundance of heavier elements reflects the composition of the envelope of the young star (*1*) which in turn is a measure of the composition of the interstellar medium from which the star condensed. Because these objects are recently formed, the interstellar medium giving rise to them has been contaminated by debris from previous generations of stars; hence the abundance of heavier elements is similar to that of the sun.

For extragalactic jets the situation is much less definite. If the jet has a nonrelativistic "thermal" component of ionized plasma, and if it is permeated by a roughly homogeneous magnetic field, then in principle a measure of the jet density can be obtained from observations of how the polarized component of the synchrotron radiation changes as a function of frequency. However, this Faraday rotation of the polarization angle yields the product of the number density times the component of the magnetic field along the line of sight, integrated over that path. Hence a determination of the density is very dependent on the specific model, and moreover the effects of rotation due to ionized plasma surrounding, but not in, the jet must be removed. In spite of this, observations of many different jets allow order of magnitude estimates to be made (*5*), and number densities in these jets are thought to lie in the range 10^{-1} to 10^{-5} cm^{-3}. As no spectral features are observed in these jets, there are no direct measurements of elemental abundances or temperatures. They are almost surely fully ionized, and their temperatures could be very high (10^6 to 10^8 K); given the low densities and relatively small cross section of the jets, no thermal bremsstrahlung from such a hot gas would have been seen by space-borne x-ray telescopes deployed to date. An important question is the degree of "contamination" of the jet material by non-relativistic ionized gas, either from the initial composition of the jet or by its interaction with the surrounding medium. The amount of the cooler gas drastically effects the efficiency of the jet, but there is no way it can be determined from direct measurement. However, indirect estimates can be made, and these will be discussed next.

Velocity and dynamics. The velocity of the jets, their interaction with the surrounding medium, and their composition are all related and need to be understood before the jet can be characterized. The first requirement is an estimate of the initial velocity of the jet as it emerges from its region of formation. For stellar jets this is fairly straightforward, since measurement of the Doppler shift of the observed recombination lines provides the velocity component along the line of sight. The geometry of the jet and in some cases observations of a surrounding accretion disk can then be used to estimate the inclination of the jet to the line of sight and to derive the total velocity. Velocities of a few hundred kilometers per second are found for such jets.

For extragalactic jets the picture is again less clear. For a subclass of radio-emitting galaxies and QSOs there is indirect determination of outflow velocity in some cases. These radio sources are very small, centered on the nucleus, with very high surface brightness. Their luminosity often varies with time, and extremely high resolution interferometry with intercontinental baselines has revealed motion in the plane of the sky for some objects (*11*). A naïve interpretation of this motion results in velocities greater than the speed of light ("superluminal" motion), but these results can be explained by relativistic motion of a jet which is directed very nearly along the line of sight to a distant observer (*12*). Hence there is some evidence that the initial outflow velocity from the nucleus of the parent object may be at relativistic speeds. (Note that this is bulk relativistic flow, as opposed to slower motion of a jet containing relativistic electrons.) However, not *all* compact radio sources exhibit time variations or have been seen to display proper motion in the plane of the sky. This evidence for relativistic motion near the nucleus has given rise to the idea of a "unified" model of extragalactic jets which assumes that all jets move relativistically throughout most of their length (*13*). The differences in observed morphology, including the asymmetrical double jets shown in Fig. 3, then arise only from differences in the angle between the jets and the line of sight; jets viewed "end on" are seen as the compact, variable radio sources, asymmetric jets are somewhat inclined to the line of sight, and equal jets lie in the plane of the sky.

The only other clue to jet velocity in the radio sources comes from the observed morphology. Many large-scale jets display bright knots, bends, "wiggles," and a general plume-like configuration which is strongly suggestive of slow, perhaps subsonic, motion far removed from the relativistic regime. This morphology suggests that further insight can be gained by considering some overall characteristics of the flows. A particularly useful parameter is the Reynolds number, $Re = UL/\nu$, where U is a "typical" velocity, L a scale length of the flow, and ν the kinematic viscosity. If the magnetic fields in the jets are not dynamically important ($B^2/8\pi < \rho U^2$) then the Reynolds numbers are huge even for the most modest of flow velocities. For example, conservative flow velocities of $\sim 10^7$ cm s^{-1} and jet radii of a few parsecs give Reynolds numbers of order 10^{20} or greater (*14*). Globally, it is almost certain that $B^2/8\pi < \rho U^2$ for the extragalactic jets. If this were not so, then either the magnetic pressure would disrupt the jet or the jet would have to be moving along preexisting ordered field lines anchored both at the nucleus and in some invisible medium beyond the end of the jet well outside the parent galaxy. Such a configuration seems highly contrived. However, as discussed below, there may be some evidence that *locally* the magnetic field may be dynamically important.

Flows with Reynolds numbers in this range are unstable to the onset of turbulence (*14, 15*), and it seems highly likely that the boundary layer separating the jet from the ambient medium is characterized by fully developed turbulence. This will be the case for both stellar and extragalactic jets. The existence of this turbulent boundary layer has significant consequences for the overall jet dynamics and for the requirements placed on the central "engine." Two characteristics of the boundary layer are responsible for this. First, such layers entrain material into the jet from the surrounding medium, and second, this entrainment process transfers momentum to the ambient medium and causes the jet to decelerate (*16, 17*). At such high Reynolds numbers the boundary layer expands into the jet with an opening angle proportional to M^{-1}, where M is the Mach number of the flow relative to the sound speed in the jet. Hence large-scale jets will be fully turbulent over much of their length, and the material entrained in the boundary layer becomes mixed throughout the jet.

Numerical simulations and laboratory experiments show that the mass entrainment rates are a function of both the jet velocity and the ratio of the gas density inside the jet to the density of the ambient medium, but that significant entrainment always occurs at such high Reynolds numbers. In general, the absolute entrainment rate per unit length increases with increasing jet velocity and decreases as the jet becomes less dense than the surrounding medium. The efficiency of entrainment has the opposite tendency (*14*). The momentum transfer resulting from the entrainment process causes the jet as a whole to decelerate, producing an exponentially decreasing velocity profile with distance along the jet; $v(x) = v_o e^{-x/x_o}$. The deceleration length x_o is directly proportional to the efficiency of entrainment.

It is this strong interaction which makes it unlikely that extragalactic jets, if originally relativistic, can maintain relativistic velocities over a significant fraction of their length, and it thus casts serious doubt on the simple version of the "unified" model described above. Moreover, the most efficient relativistic jets are "clean," carrying only the relativistic particles needed to produce the observed radiation, and these jets are also "light" or less dense than the ambient intracluster or circumgalactic medium and hence are the most easily decelerated. Observational evidence for this boundary layer formation has been recently obtained with state of the art detectors at large telescopes (*18, 19*). These observations show regions of atomic recombination line radiation arising along the edge of the radio emitting jets and lobes in many radio galaxies, and this emission is what could be produced by the heating and ionization of the ambient interstellar or intracluster medium after the passage of a supersonic jet. This optical line emission is not universal; it tends to be associated with jets with complex morphology and lower radio luminosity, which is again consistent with strong interaction and deceleration by the ambient medium.

Figure 6 illustrates another form of interaction of extragalactic jets with the ambient medium. Large, rich clusters of galaxies with 10^3 or more members have been observed by space-borne x-ray telescopes to frequently contain a hot dense ionized intracluster medium, with temperatures of 10^8 K and central densities of 10^{-2} to 10^{-3} particles cm^{-3}. If the clusters are in equilibrium the virial velocities of the cluster members are $\sim 10^3$ km s^{-1}, and in fact these velocities are measured for such cluster galaxies. The radio galaxy shown in Fig. 6 is called a "head-tail" radio source, and this particular morphology is found only in radio sources occurring in rich clusters. The straightforward interpretation of this phenomenon is that the jets are emerging roughly perpendicular to the galaxy's velocity vector, and that the ram pressure of the intracluster medium due to the galaxy motion causes the jets to be swept back. This interaction is very fortuitous because it allows some limits to be placed on the previously unmeasured jet velocity and density, since the bending radius, ambient density, and galaxy velocity are all known reasonably well. Early order of magnitude estimates for this effect proved insufficient because no jet deceleration was included; subsequent numerical simulations showed this to be a significant effect. These modeling efforts yield likely jet velocities of about $0.1c$ or less and jet number densities of 10^{-1} to 10^{-3} particles cm^{-3} in order to match the observed bending radius (*20*).

A similar class of jet-environment interaction is shown by the example in Fig. 5. These "wide-angle tailed" sources also occur in clusters of galaxies, but the origin of the jet bending in this case is much less clear. These jets arise in slowly moving galaxies in the center of clusters, and the sudden jet bending, together with the marked asymmetry of the jets, seems to rule out deflection by ram pressure attributable to galaxy motion. The jets in these sources often have bright spots where the bending occurs, and this has led to the idea that deflection is caused by the jet striking a dense cloud or density enhancement in the intracluster medium. However, recent numerical simulations have shown that such clouds must be as massive as dwarf galaxies for the deflection to persist long enough to agree with the observed jet length after the bending occurs. Otherwise the cloud is eroded away by the jet. There is no observational evidence of any galaxy being present at the point of deflection, and thus it is difficult to understand how such dense massive clouds could exist in the hot intracluster medium without collapsing into a small galaxy of stars or evaporating away. Thus the origin of the bending of these wide-angle jets remains unresolved.

Magnetic fields. The presence of any significant amount of magnetic energy has not been detected within stellar jets. However, there is some evidence of magnetic fields in the surrounding interstellar medium, and the field geometry seems aligned along the jet (*21*). It is not clear yet if this field is strong enough to play a role in the collimation of the stellar jets, or if it is a weaker ambient field whose alignment is a result of its being swept up by the passage of the more dominant jet.

As discussed above, extragalactic jets are probably not globally dominated by magnetic fields. However, there are some regions in the jet of M87 where confinement of the jet by strong magnetic fields may indeed be occurring (*22*). The origin and maintenance of the current systems required to produce such self-pinched jet confinement is not understood at this time. The magnetic field geometries in extragalactic jets can be deduced from the polarization properties of the synchrotron radiation. In general the magnetic fields are either parallel or perpendicular to the jet, and some have the field perpendicular to the jet near the center of the jet and more parallel near the edges. The more luminous jets tend to have the field parallel to the jet as do most sources with "one-sided" jets (*5*). Estimates of magnetic field strengths can be obtained by assuming the minimum total energy in the radio source is present to produce the synchrotron radiation. This assumption results in roughly equal energies in the relativistic electrons and magnetic fields, and such "equipartition" field strengths range from 10^{-4} to 10^{-6} G.

Similar estimates of field strengths can be made for the large double-lobed emitting regions, and flux conservation arguments show that convection of field by jets into these large volumes would, in many cases, result in field strengths well below the equipartition values of 10^{-5} to 10^{-6} G. The solution to this problem may lie in the extragalactic jets and their interaction with the surrounding medium. If a small "seed" field is convected into the lobes by the jets, then the turbulence generated by the kinetic energy of the jets can drive a fully turbulent dynamo which can amplify the small magnetic field up to its equipartition value (*23*). Non-linear calculations of this effect show this to be most effective for "heavy" jets with density comparable to or greater than that of the ambient medium, and that the field is readily amplified to equipartition values on scales up to the jet diameter in times short compared to the nominal jet lifetimes of $\sim 10^8$ years. To create magnetic field structures on larger scales ($\gtrsim 10$ kpc) requires injection of kinetic helicity as well as kinetic energy if this is to be accomplished in 10^8 years. Such helicity could come from angular momentum possessed by the central energy source in the nucleus.

Origins. The detailed nature of the source of extragalactic jets is unknown. The above discussion suggests that jets interact strongly with the ambient medium, and hence their net efficiency in supplying the energy required to power the extended radio lobes may be rather low. This means that the central source must provide very large amounts of total energy, sometimes in excess of 10^{46} ergs s^{-1}.

A logical, but so far undetected, candidate for such a source is a massive rotating black hole of mass 10^8 solar masses or greater. Such an object could be created as the end point of the evolution of a dense stellar system in a massive galaxy or QSO, or possibly as the result of the merging of two or more galaxies in regions of high galaxy density (*24*). It is likely that the black hole will be surrounded by copious amounts of gaseous debris after its formation, and it is equally likely that this gas possesses sufficient angular momentum to form a disk or torus around the black hole. This gas can then accrete onto the black hole, releasing a large amount of energy in the process. If the black hole is also spinning, magnetic torques can extract some of this rotational energy up to a maximum of about 30% percent of the rest mass energy, and the twisting magnetic fields threading the accretion disk can also serve to accelerate and initially collimate gas driven off the disk by radiation pressure (*25*). It is known that jets exist on parsec size scales in the nucleus; whether a single collimation process maintains this jet configuration out to a million times this size is not clear.

This qualitative picture of the formation of a black hole, its attendant accretion disk and subsequent formation of jets is attractive because it uses known physics and is possible in principle. Whether such a model can be consistent with production of up to 10^{46} ergs per second of energy in very specialized form is not yet known. The important point is that careful observations and modeling of the jets themselves are providing more stringent boundary conditions which must be met by any successful models of the central power source.

Cosmology. If this general picture of the origin of astrophysical jets is correct, then they are created only after a significant amount of evolution of the parent galaxy or QSO has occurred. If so, then the recent discoveries of very high redshift radio galaxies such as the one shown in Fig. 7 may pose serious challenges to contemporary cosmological models. Given the standard Big Bang model, the galaxies seen at redshifts of nearly 4 are in a universe less than 20% of its present age. Thus any successful cosmological model must be able to create a density fluctuation that can separate from the overall Hubble expansion, collapse into a galaxy and form stars, condense the central region enough to form a massive black hole, form the radio jets, and have those jets travel out to feed the radio lobes at ~100-kpc separation all by the time the universe is 10 to 20% of its present age, a period of about 10^9 years. Another constraint on this overall picture comes from recent observations of the cosmic microwave background. These observations have not yet detected any fluctuations in this background which would be the signature of the small density perturbations necessary at that very early epoch to cause later collapse into galaxies and clusters of galaxies. If this result persists, then the observed radio galaxies at high redshift must come from density fluctuations which occurred after the decoupling of radiation and matter in the very early universe. As 10^9 years is only ten galactic "years" or rotation periods, it is not clear that all of this (that is, the construction of a galaxy with extended radio lobes) can be accomplished in that time. If radio galaxies at very high redshifts ($z \approx 5$) are discovered in the future, then current cosmological models may have to undergo considerable revision.

REFERENCES AND NOTES

1. R. Mundt, in *Protostars and Planets II,* D. Black and M. Matthews, Eds. (Univ. of Arizona Press, Tucson, 1985), pp. 414–433.
2. P. Hartigan, *Astrophys. J.* **339**, 987 (1989).
3. R. Lovelace and H. Berk, in preparation.
4. A Pacholczyk, *Radio Astrophysics* (Freeman, San Francisco, 1970).
5. A. Bridle and R. Perley, *Annu. Rev. Astron. Astrophys.* **22**, 319 (1984).
6. R. Blandford and M. Rees, *Mon. Not. R. Astron. Soc.* **169**, 395 (1974).
7. P. J. McCarthy and W. van Breugel, in *The Epoch of Galaxy Formation,* C. Frenk, R. Ellis, T. Shanks, A. Heavens, J. Peacock, Eds. (Kluwer, Dordrecht, 1989), p. 57.
8. P. J. McCarthy, W. van Breugel, H. Spinrad, S. Djorgovski, *Astrophys. J.* **321**, L29 (1987).
9. R. Davies and M. Birkinshaw, *Astrophys. J. Suppl.* **68**, 409 (1988).
10. J. Borovsky and J. Eilek, *Astrophys. J.* **308**, 929 (1986).
11. S. Unwin *et al.*, *ibid.* **271**, 536 (1983).
12. M. J. Rees, *Mon. Not. R. Astron. Soc.* **135**, 345 (1967).
13. P. Barthel, *Astrophys. J.* **336**, 606 (1989).
14. D. S. De Young, *ibid.* **307**, 62 (1986).
15. L. D. Landau and E. M. Lifshitz, *Fluid Mechanics* (Addison-Wesley, Reading, 1959), pp. 103–121.
16. A. A. Townsend, *The Structure of Turbulent Shear Flow* (Cambridge Univ. Press, New York, 1956), pp. 172–200.
17. G. Brown and A. Roshko, *J. Fluid Mechanics* **64**, 775 (1974).
18. S. Baum and T. Heckman, *Astrophys. J.* **336**, 702 (1989).
19. G. Miley, T. Heckman, H. Butcher, W. van Breugel, *ibid.* **247**, L5 (1981).
20. D. S. De Young, *ibid.,* in press.
21. S. Strom and K. Strom, in *IAU Symposium 115,* M. Peimbert and J. Jugakee, Eds. (Reidel, Dordrecht, 1986).
22. F. N. Owen, P. Hardee, T. Cornwell, *Astrophys. J.* **340**, 698 (1989).
23. D. S. De Young, *ibid.* **241**, 81 (1980).
24. M. Begelman, R. Blandford, M. Rees, *Rev. Mod. Phys.* **56**, 255 (1984).
25. R. Lovelace, *Nature* **262**, 649 (1976).
26. R. Perley, J. Dreher, J. Cowan, *Astrophys. J.* **285**, L35 (1984).
27. J. Burns, *Mon. Not. R. Astron. Soc.* **195**, 523 (1981).
28. D. S. De Young, *Annu. Rev. Astron. Astrophys.* **14**, 447 (1976).
29. K. Chambers, G. Miley, R. Joyce, *Astrophys. J.* **329**, L75 (1988).

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