Chapter 13

Astrophysical Jets

In an astrophysical context, **jets** may be defined as well-collimated outflows from a compact object. Jets are commonly bipolar, with two back-to-back jets streaming away from the central compact object. There are two types of astrophysical jets on which attention has been focused.

1. **Young stellar jets** are seen near newly forming stars. The length of a young stellar jet is $l = 0.01 \rightarrow 1\,\mathrm{pc}$, and the velocity of gas within the jet is $v = 100 \rightarrow 400\,\mathrm{km\,s^{-1}}$; the central compact object is a newborn star of mass $M \sim 1\,\mathrm{M_\odot}$. A young stellar jet carries off mass at a rate $\dot{M} = 10^{-9} \rightarrow 10^{-6}\,\mathrm{M_\odot\,yr^{-1}}$.

2. **Extragalactic jets** are seen near the nuclei of radio galaxies and quasars. The length of an extragalactic jet is $l = 0.01 \rightarrow 1\,\mathrm{Mpc}$, and the velocity of gas within the jet may be as high as $v \sim c$; the central compact object is (probably) a black hole of mass $M = 10^8 \rightarrow 10^9\,\mathrm{M_\odot}$.

Despite the very different length scales and velocities for the two types of jets, the basic physics involved is the same. Long, highly collimated flows originate in a compact object, and appear to be perpendicular to an accretion disk. In addition to a force that counteracts the gravitational force of the central compact object, the formation of a jet requires a 'nozzle' to shape the gas flow into a narrow jet. Theorists have divided the study of astrophysical jets into two parts. (1) What forces act to accelerate and collimate the beam? (2) How does the jet propagate through space once it has been accelerated and collimated? The first question is the more difficult one. Jets are presumably accelerated by one of the mechanisms that accelerate winds: jets might be pressure-driven, radiation-driven, Alfven-wave-driven, or shock-driven. No one is sure how jets are collimated; by the time they are visible to observers, they are already tightly collimated. Because of our vast ignorance of how jets are born, theoretical studies have focused on the question of how jets propagate through space once they are born.

Young stellar jets have more observational data than extragalactic jets to constrain any models that we may make. For instance, spectroscopy of stellar jets gives information about the bulk velocity, velocity dispersion, electron density, and line excitation as a function of position along the jet. Extragalactic jets, however, do not emit line radiation, so we cannot use Doppler shifts and Doppler widths to measure the bulk velocity and velocity dispersion within the jet. We will focus our attention on the better-known young stellar jets.

Stars form in molecular clouds, where the temperature is $T \approx 10\,\mathrm{K}$, and the sound speed is $a \approx 0.3\,\mathrm{km\,s^{-1}}$. The molecular clouds contain dense cores that are supported by magnetic pressure. As the magnetic field slowly diffuses outward, the core collapses to form a rotating protostar, which accretes matter both from an accretion disk and from a roughly spherical infall of gas and dust. When the protostar becomes sufficiently massive, deuterium burning ignites, and a stellar wind starts to push its way outward. At first, the stellar wind is contained by the infalling matter, which has been compared to the lid of a pressure cooker. Eventually, the ram pressure of the stellar wind breaks through the 'lid' at its weakest points, the rotational poles of the protostar (where the column depth of accreting matter is smallest). The next stage is a young stellar object, with jets flowing outward along the two rotational poles, and an accretion disk lying in the equator. The opening angle of the jet widens with time, until the young stellar object becomes an optically visible T Tauri star.

The jet associated with a young stellar object remains tightly collimated for some length, then expands outward in a 'stellar wind cavity'. The cavity ends at a working surface, where the jet flow is decelerated by a shock. The basic morphology of a young stellar jet is shown in Figure 13.1. The shock heating at the working surface creates a **Herbig-Haro object**, which is a low-excitation emission-line nebula. The working surface of the jet moves outward at a velocity u_w with respect to the central star. The velocity u_w depends on the bulk velocity u_j of matter within the jet, and on the ratio $\eta \equiv \rho_j/\rho_0$, where ρ_j is the gas density within the jet and ρ_0 is the density of the ambient medium. In a frame of reference fixed to the working surface

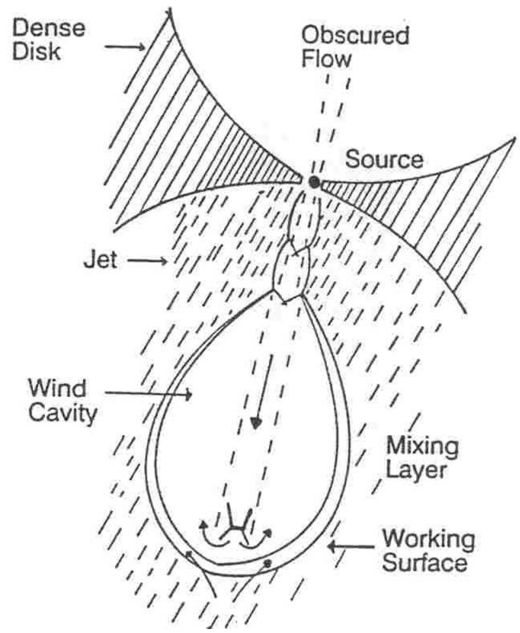

Figure 13.1: The components of a typical jet from a young stellar object.

of the jet, the ambient gas is moving with a velocity $-u_w$ and the jet gas is moving with a velocity $u_j - u_w$. Since the working surface is stationary in this frame, the ram pressure of the gas on the two sides of the working surface must be equal. That is,

$$\rho_j(u_j - u_w)^2 = \rho_0 u_w^2 \ . \tag{13.1}$$

This yields a quadratic equation for u_w,

$$(\eta - 1)u_w^2 - (2\eta u_j)u_w + \eta u_j^2 = 0 \ , \tag{13.2}$$

of which the positive root is

$$u_w = u_j \frac{\eta^{1/2}}{1 + \eta^{1/2}} \ . \tag{13.3}$$

For heavy jets, with $\eta \gg 1$, the working surface moves outward with a velocity $u_w \approx u_j$. For light jets, with $\eta \ll 1$, the working surface moves outward with the low velocity $u_w \approx u_j \eta^{1/2}$. Observations of the velocities of young stellar jets, and of the Herbig-Haro objects at their working surfaces, indicate that $\eta \sim 1-2$. The density of hydrogen atoms in the stellar jet and in the ambient molecular cloud are $n \sim 50\,\mathrm{cm}^{-3}$.

The age of a young stellar jet, as deduced from its expansion velocity, is

$$t_j \approx 10^3\,\mathrm{yr}\left(\frac{R}{0.1\,\mathrm{pc}}\right)\left(\frac{u_w}{100\,\mathrm{km\,s^{-1}}}\right)^{-1}, \tag{13.4}$$

where R is the length of the jet. The mass of the jet is

$$M_j \approx 10^{-4}\,\mathrm{M}_\odot\left(\frac{R}{0.1\,\mathrm{pc}}\right)\left(\frac{u_w}{100\,\mathrm{km\,s^{-1}}}\right)^{-1}\left(\frac{\dot{M}}{10^{-7}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}}\right), \tag{13.5}$$

and its kinetic energy is

$$E_j \approx 10^{43}\,\mathrm{erg}\left(\frac{R}{0.1\,\mathrm{pc}}\right)\left(\frac{u_w}{100\,\mathrm{km\,s^{-1}}}\right)\left(\frac{\dot{M}}{10^{-7}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}}\right), \tag{13.6}$$

as long as $\eta \gtrsim 1$ and $u_w \approx u_j$. During the jet's lifetime, the energy carried away from the star by photons is

$$Lt_j \approx 10^{44}\,\mathrm{erg}\left(\frac{R}{0.1\,\mathrm{pc}}\right)\left(\frac{u_w}{100\,\mathrm{km\,s^{-1}}}\right)^{-1}\left(\frac{L}{1\,\mathrm{L}_\odot}\right), \tag{13.7}$$

so the energy carried away by the jet can be comparable to the energy carried away by radiation.

A bit of gas that is ejected into the jet moves away from the star at a velocity u_j until it reaches the working surface. The gas is then shocked and heated, and enters a cocoon of hot gas that surrounds the jet. Conservation of mass implies that the mass of the cocoon increases at the rate $\dot{M}_{\mathrm{coc}} = \rho_j(u_j - u_w)A_j$, where A_j is the area of the working surface. The cocoon increases its mass at the rate

$$\dot{M}_{\mathrm{coc}} = \frac{\rho_j u_j A_j}{1+\eta^{1/2}}, \tag{13.8}$$

while the jet itself increases its mass at the rate

$$\dot{M}_j = \rho_j u_w A_j = \eta^{1/2}\frac{\rho_j u_j A_j}{1+\eta^{1/2}}. \tag{13.9}$$

If the rates of mass gain are constant, the ratio of the cocoon mass to the jet mass is

$$M_{\mathrm{coc}}/M_j = \eta^{-1/2}. \tag{13.10}$$

In addition to the dependence on the density ratio η, the structure of the jet also depends on its Mach number $N_j = u_j/a_j$, where $a_j = (\gamma P_j/\rho_j)^{1/2}$s. Jets with low Mach numbers have cocoons that extend only a short distance from the working surface; jets with high Mach numbers have cocoons that extend for the entire length of the jet. Figure 13.2 shows a series of jet simulations; all the jets have Mach number $m_j = 6$, but their value of η ranges from $\eta = 10$ (no cocoon worth mentioning) to $\eta = 0.01$ (a cocoon much larger than the central jet). Figure 13.3 shows a series of jet simulations in which all the jets have $\eta = 0.1$, but their Mach number ranges from $m_j = 1.5$ (short cocoon) to $m_j = 12$ (cocoon as long as the jet).

Since the jet has an internal pressure P_j, what keeps the jet from expanding perpendicular to its long axis? In non-magnetic jets, the confinement is provided by the external pressure P_{ex}. If the pressure of the external medium is constant, then the diameter d of the jet is roughly constant as a function of the distance r along the jet. If, however, the external pressure P_{ex} varies with distance along the jet, the diameter of the jet will vary in order to maintain pressure equilibrium at the sides of the jet. Suppose that the gas within the jet is polytropic, with

$$P_j = P_0(\rho_j/\rho_0)^\gamma \ . \tag{13.11}$$

If the external pressure has a power-law dependence on r,

$$P_{ex} = P_0(r/r_0)^{-n} \ , \tag{13.12}$$

then the requirement that $P_j = P_{ex}$ yields a density profile

$$\rho_j(r) = \rho_0(r/r_0)^{-n/\gamma} \ . \tag{13.13}$$

If the mass flux $\dot{M}$ and the bulk velocity u_j are constant along the jet, then the mass continuity relation

$$\dot{M} = \frac{\pi}{4} d(r)^2 \rho_j(r) u_j \tag{13.14}$$

tells us that

$$d(r) = \left(\frac{4\dot{M}}{\pi u_j \rho_0}\right)^{1/2} \left(\frac{r}{r_0}\right)^{n/(2\gamma)} \ . \tag{13.15}$$

The opening angle θ of the jet is $\theta \approx d/r$ as long as $d \ll r$. When the jet is narrow,

$$\theta(r) = \theta_0 \left(\frac{r}{r_0}\right)^{(n-2\gamma)/(2\gamma)} \ . \tag{13.16}$$

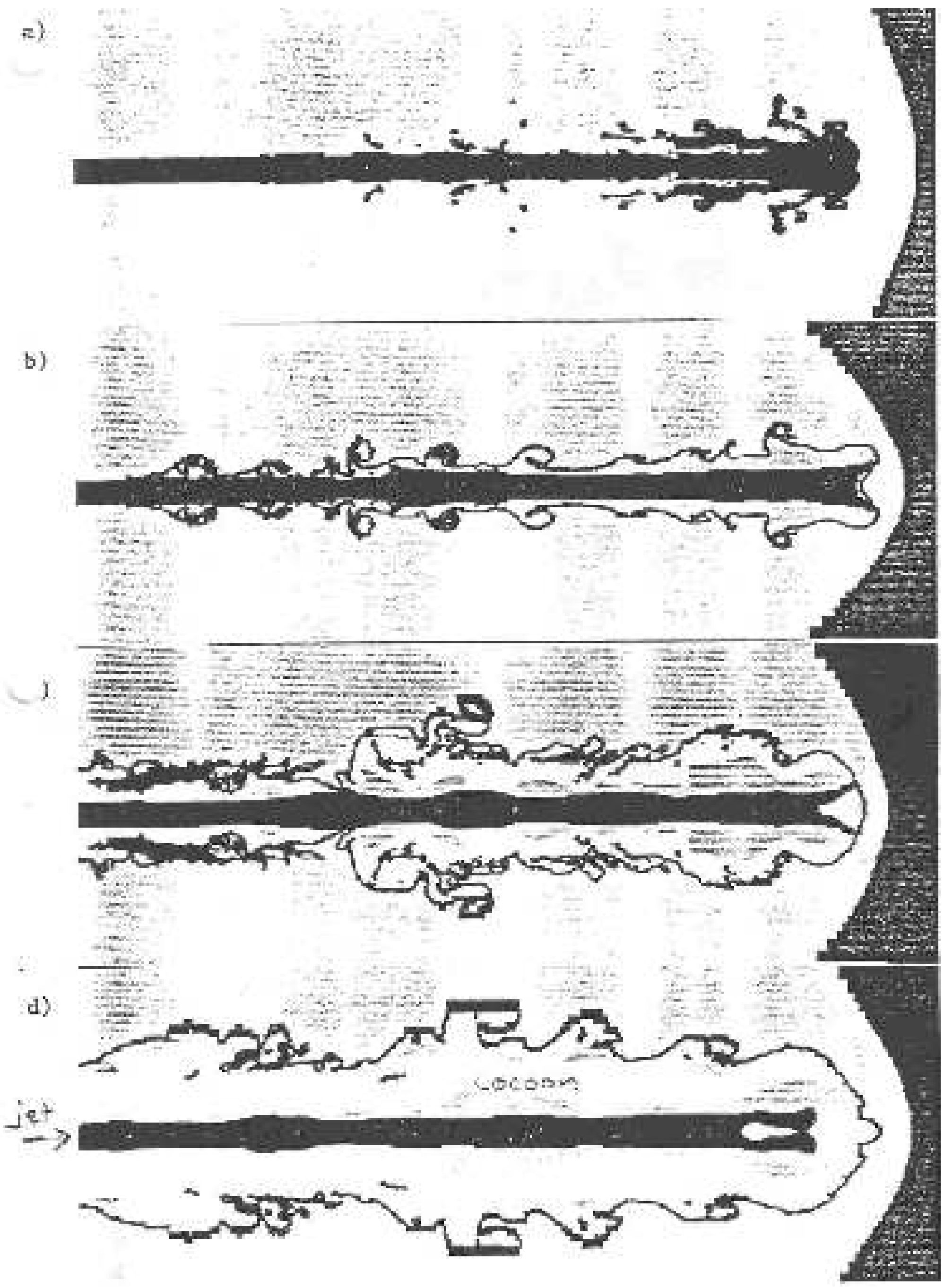

Figure 13.2: A sequence of simulated $m_j = 6$ jets, with $\eta = 10$, 1, 0.1, and 0.01 (top to bottom).

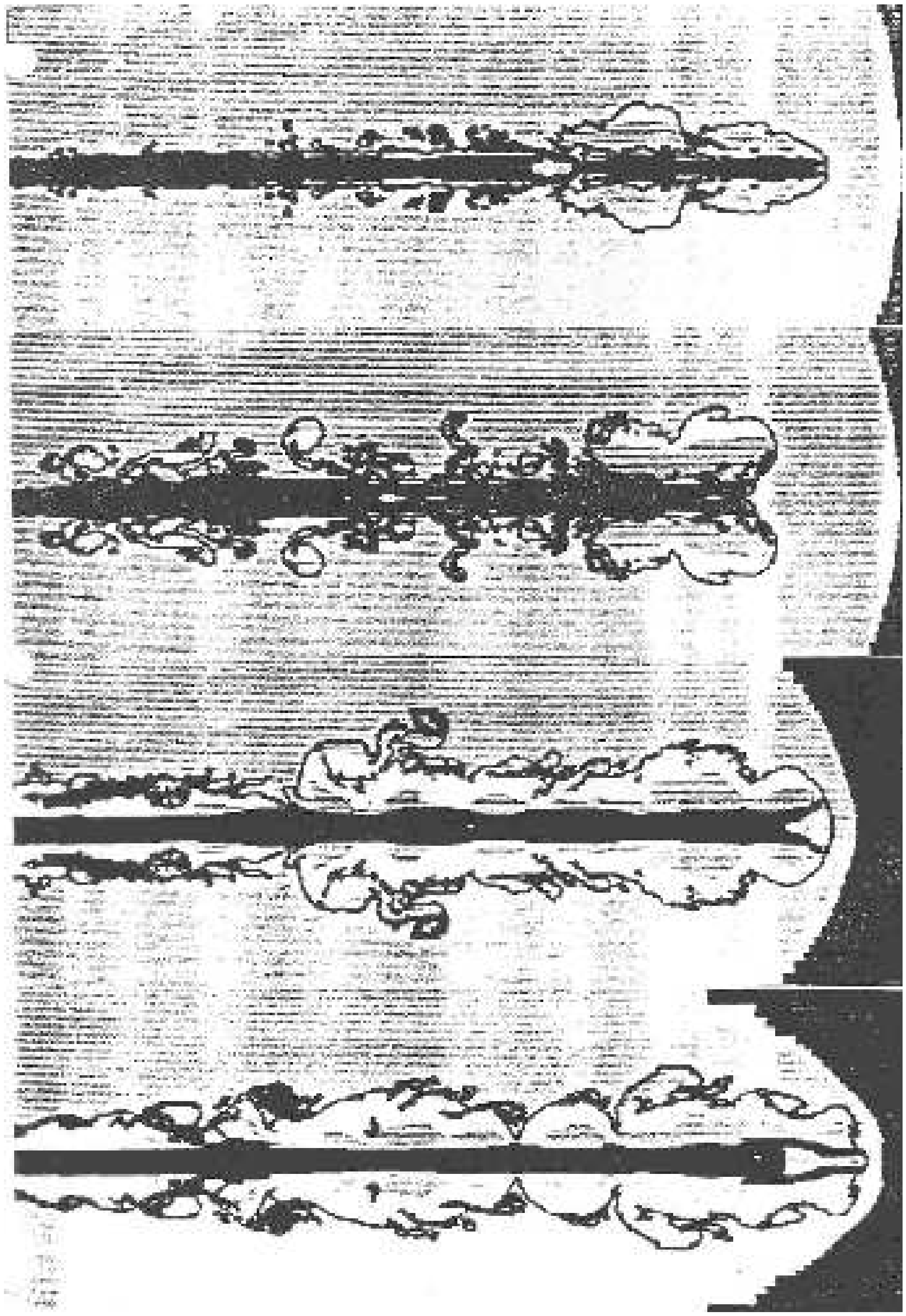

Figure 13.3: A sequence of simulated $\eta = 0.1$ jets, with $m_j = 1.5$, 3, 6, and 12 (top to bottom).

The Mach number m_j of the jet is

$$m_j = u_j \left(\frac{\gamma P_j}{\rho_j}\right)^{-1/2} = m_0 \left(\frac{r}{r_0}\right)^{n(\gamma-1)/(2\gamma)} . \qquad (13.17)$$

When $\gamma > 1$, the Mach number of the jet increases as the external pressure decreases.

If the jet has a very high Mach number, or is very broad, it can no longer be confined by the pressure of the ambient medium. Place yourself in a frame of reference traveling along the axis of symmetry of the jet with the gas velocity u_j. In this frame of reference, the walls of the jet are moving away from you with a velocity

$$u_{\rm wall} \approx u_j \tan\left(\frac{\theta}{2}\right) \approx u_j \frac{\theta}{2} . \qquad (13.18)$$

Information about changes in the external pressure are carried toward you from the wall of the jet with a velocity equal to the sound speed a_j. In order for the jet to remain confined by the pressure of the outside gas, it must remain in causal contact with the gas outside the walls of the jet. This requires that $u_{\rm wall} < a_j$, or, in other words, that $\theta m_j < 2$. In our model with $P_{ex} \propto r^{-n}$, the product of the opening angle θ and the Mach number m_j is

$$\theta m_j = \theta_0 m_0 \left(\frac{r}{r_0}\right)^{(n-2)/2} . \qquad (13.19)$$

Thus, when $n > 2$, there will be a critical radius r_f at which $\theta m_j = 2$; beyond this point, the jet will no longer be confined by the pressure of the ambient medium. It will be a **free jet**. Free jets have a constant opening angle

$$\theta_f = \frac{2}{m_j(r_f)} . \qquad (13.20)$$

The diameter of the free jet will increase at the rate $d \propto r$, the density will decrease at the rate $\rho_j \propto r^{-2}$, and the Mach number will increase at the rate $m_j \propto r^{\gamma-1}$. Some extragalactic jets have a constant opening angle, and are conjectured to be free jets. One such jet is seen in NGC 6251 (Figure 13.4).

Radiative cooling can have an important effect on the structure of stellar jets. Cooling creates a dense, cool shell at the head of the jet. The density within the shell, simulations indicate, can be as much as 100 times the density

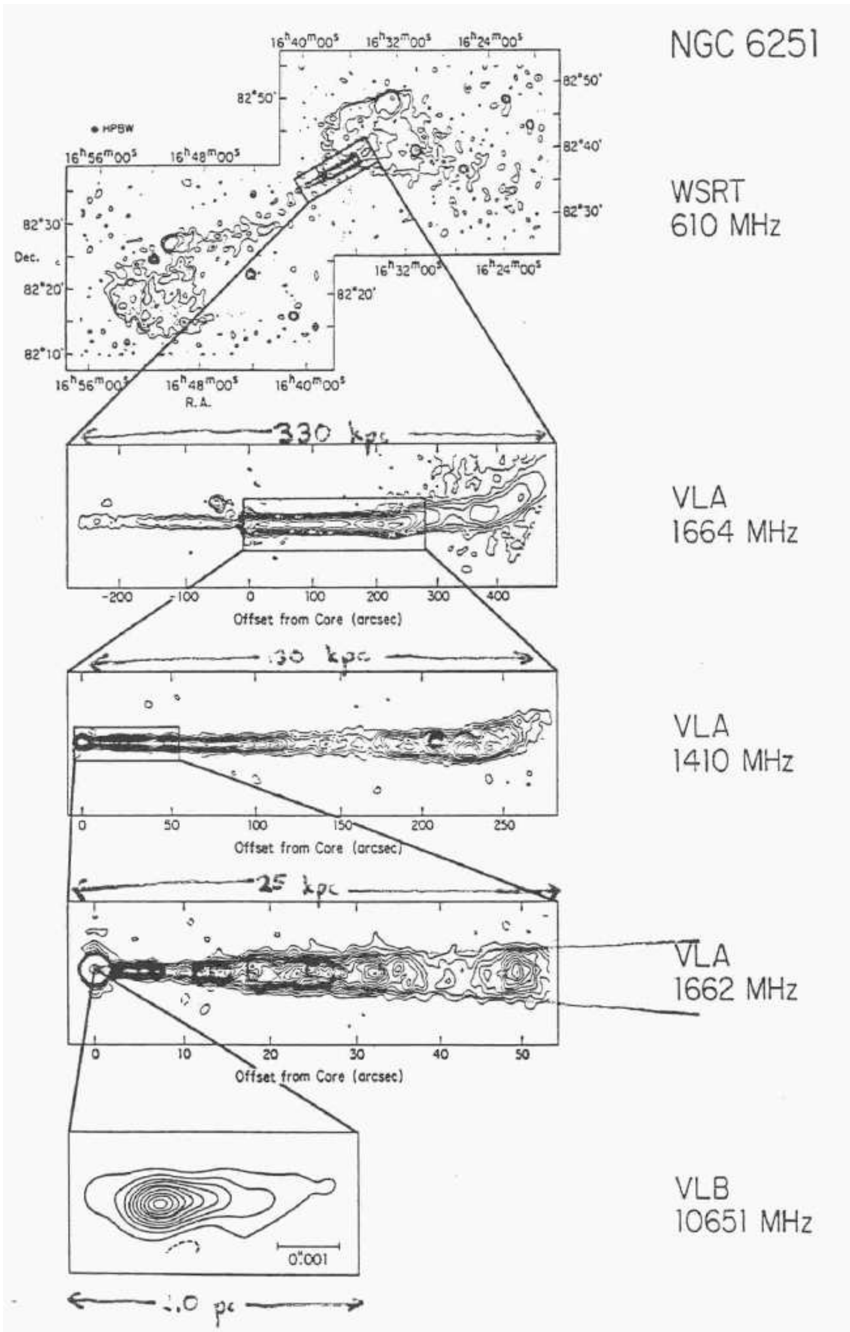

Figure 13.4: The jet of the radio galaxy NGC 6251, seen at radio frequencies at over a wide range of angular resolutions.

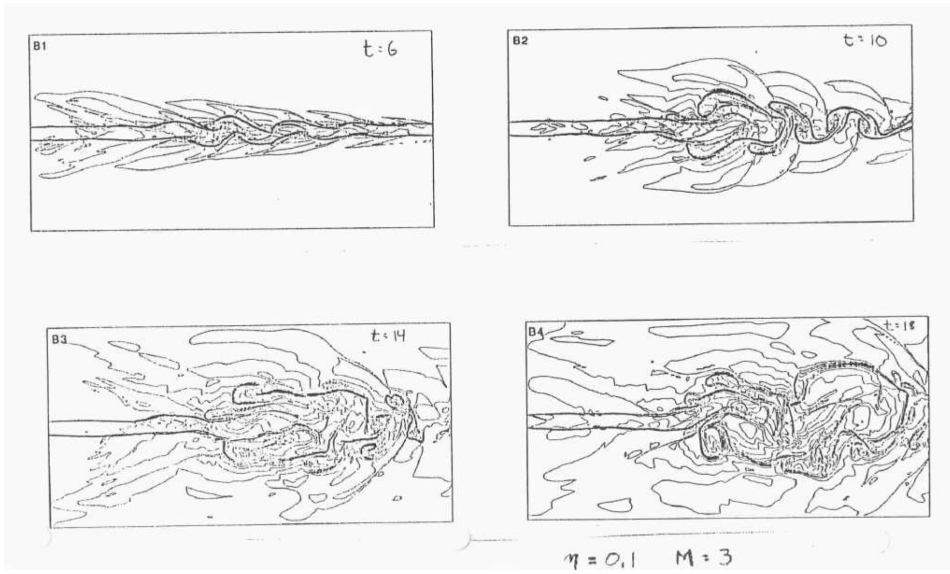

Figure 13.5: A numerical simulation of the growth of jet instabilities. Note that periodic wiggles grow into turbulent eddies. [Norman & Hardee (1988) APJ, 334, 80]

of the ambient medium. This radiating, dense shell can be identified with Herbig-Haro objects seen at the ends of young stellar jets. Cooling also decreases the size and the pressure of the cocoon.

Jets are not perfectly smooth and straight; they show a tendency to break up into knots and to deviate into 'wiggles'. These knots and wiggles can occur because the jet is subject to instabilities that are analogous to the classic Kelvin-Helmholtz instability. Figure 13.5 shows the development of jet wiggles in a numerical simulation. Numerical studies indicate that there exist growing modes of instability for jets with any Mach number. Some of these modes are axisymmetric, pinching modes (these would tend to give rise to observed knots) and some modes are nonaxisymmetric helical modes (these would tend to give rise to observed wiggles). The fastest growing modes are those with wavelengths comparable to the diameter d of the jet (this is why knots are roughly circular and wiggles have radii of curvature roughly equal to the jet width).