# 1

# Introduction

## 1.1 Rudimentary definitions and concepts

A man-made jet is a narrow stream forced out of a designed aperture or nozzle. Water fountains and jet engines provide everyday examples of liquid and gas jets. Skin penetration and rock drilling are high-technology applications. Jets also occur naturally on the Earth associated with geysers and some types of volcanic eruption. These terrestrial jets arise when material is raised to a high pressure below the surface and is forced to ascend through channels with rigid walls. In contrast, the astrophysical jet involves relatively unfamiliar physics, usually under extreme, but occasionally in exotic, conditions.

In astronomy, there is rarely a solid nozzle or tube to align the jet flow. The material is driven, with a few exceptions, through an interacting gas. In other words, an astrophysical jet is a slender channel of high-speed gas propagating through a gaseous environment. The exceptional jets are the nearest extraterrestrial jets associated with comets such as Hale-Bopp. In the latter case, as for those shown in Fig. 1.1, they are believed to form when a high-pressure mixture of gas and dust breaks through vents in a solid crust.

Astrophysical jets are driven from diverse objects on very different size and mass scales. They can be produced from the vicinity of supermassive black holes in the case of active galactic nuclei (AGN), by star-sized black holes in microquasars, by neutron stars in some X-ray binaries, by protostellar cores in young stellar objects, and by white dwarfs in symbiotic binaries and supersoft X-ray sources. The 'material' of these astrophysical jets is much more than a simple compressible fluid or gas. The gas may consist of a mixture of ions, electrons, molecules and dust particles, or can be dominated by a magnetic field and relativistic particles. The complete quantitative inventory has proved remarkably difficult to establish in all cases.

The truly remarkable fact is that, despite a lack of rigidity, the materials and forces conspire to generate jets with high thrust and power from all these astrophysical objects. The thrust is often sufficient for the jet to excavate a tunnel which transports the gas tremendous distances. For example, jets from the vicinity of supermassive black holes, located deep in the nuclei of galaxies, pierce through the interstellar medium and exit into the extragalactic medium (Fig. 1.2). The same jet is still operating, at least in the same direction, despite ten orders of magnitude (ten powers of ten) expansion. Even so, the jet phenomenon was not deemed to be reason enough by some to deserve much attention. After all, aren't these merely waste channels – the rising smoke from the chimney pots? By studying the smoke, we could never hope to discover the cause of a fire.

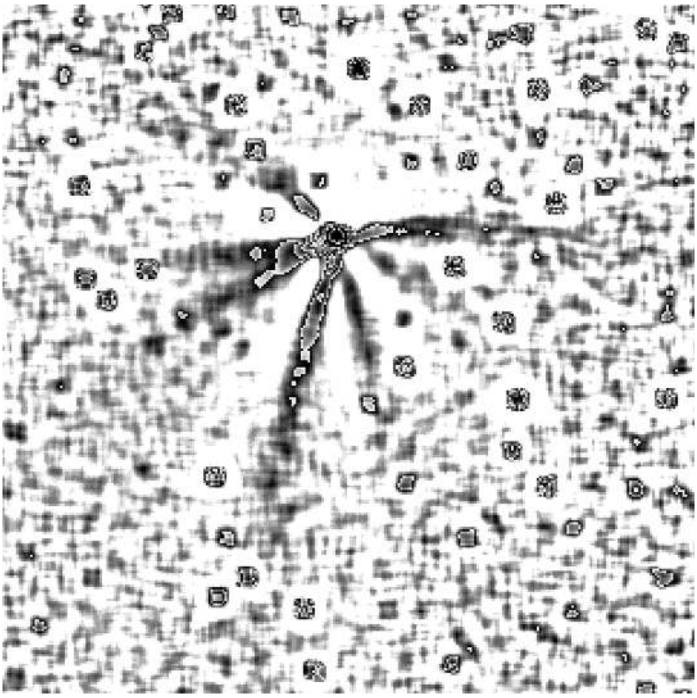

Fig. 1.1 Seven jets emanating from comet Hale-Bopp observed on 18 August 1996. The jets are detected through the reflection of sunlight by dust grains. The dust is ejected from vents on the surface due to the pressure of out-streaming gas. The 20-second CCD image with the R-filter to measure the dust has been heavily processed to suppress the smooth structure of the coma. At the time of these observations, comet Hale-Bopp was 2.761 AU from the Earth and 3.392 AU from the Sun. The image size is 320"×320". Credit: N. Thomas, H. Rauer, Danish 1.54-m telescope at La Silla, ESO.

That opinion has turned out to be a misconception. Instead, the jets must be a crucial component of our observational and theoretical interpretation. Firstly, the mass and power ejected are often significant fractions of that available. Therefore, how we trace the evolution of the central engine must be considerably modified. Secondly, the jets are now believed to extract the angular momentum from the inner contracting or collapsing zone – without the jets, centrifugal forces might suffice to support material within a spinning disc. As a consequence, a collapsed object would not so readily form.

The jets are also our beacons. Entire classes of distant objects in the universe have been made detectable through their jet activity: their luminosity is boosted by relativistic beaming for those members with jets pointing by chance in our direction. Without the jets, few or none of the objects would be powerful enough to be detected.

Even within our own galaxy, we discover and precisely locate stellar embryos through their jets. Jets from protostars, the contracting cores of gas which will eventually form the stars, cut through the thick obscuring cores and plough on through embedding giant molecular clouds. The protostar is visually obscured and their jets would also be hidden, since stars are born deep inside dense cores. Through impact with a less obscuring molecular

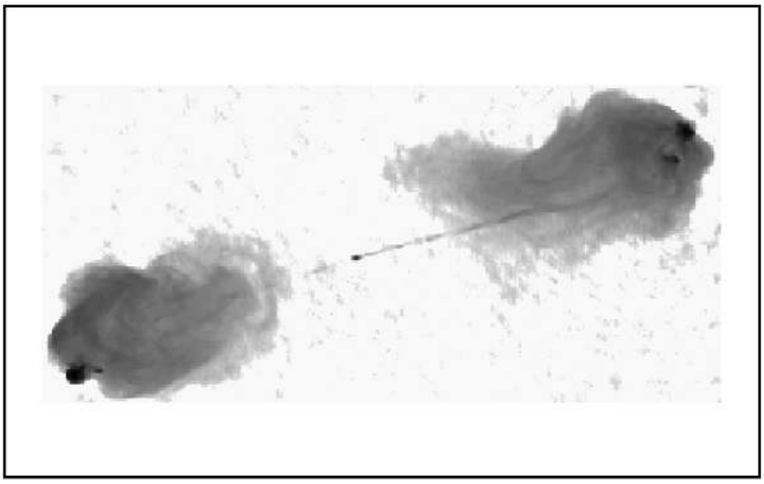

Fig. 1.2 The Cygnus A radio galaxy, catalogued as 3C 405, as observed at 5 GHz in the radio by Perley *et al*. (1984) with the Very Large Array (VLA). The resolution is 0.4". It is the closest example of a powerful double radio galaxy, identified with a cD (giant elliptical) galaxy at a redshift of $z = 0.0561$ corresponding to an angular size distance of 220 Mpc. Two kiloparsec-sized hot spots are found at the leading edge of each 60-kiloparsec lobe. Reproduced by permission of the AAS.

cloud after penetrating out of the core, molecules are heated and subsequently emit radiation at wavelengths longer than in the visible. This infrared, millimetre and radio emission is less attenuated by intervening dust grains and so a jet makes its presence known (Fig. 1.3).

Jets also provide a channel for feedback. From the cores of galaxies, they may support and sustain gas in a halo and so slow down the rate at which stars form. They may also trigger bursts of star formation in cloud complexes close to their paths. From the cores harbouring protostars, jets raise the pressure upon impact. The pressure lowers the critical mass required for surrounding clumps to gravitationally collapse. Moreover, the jet-incurred turbulence speeds up the star formation 'metabolism', enhancing both dispersal and collapse.

Besides these motivations, jets are widely exploited as laboratories within which dynamical, physical and chemical processes are examined in concentrated form. The focusing and compression lead to rapid reactions: strong heating in shock waves and swift cooling in their wakes. The product is bright compact knots of emission. Consequently, they are testing grounds in which many predictions have been verified and others forgotten.

In this introduction, we piece together the story of the discovery of jets in what has assembled into an increasingly divergent range of phenomena. This motivates the major aim of this text: to raise and study the concept of *the astrophysical jet*. Independently of specific causes and effects, jets are spectacular in display and fascinating in properties. We study them here as flow systems, searching for their common attributes and unifying phenomena.

Our definition of a jet is quite narrow and exclusive. Beams of radiation (light rays) are obviously excluded. Plumes of gas are also excluded. In fluid dynamics, plumes are features maintained by thermal buoyancy. In astrophysics, plumes refer to wide spouts which open

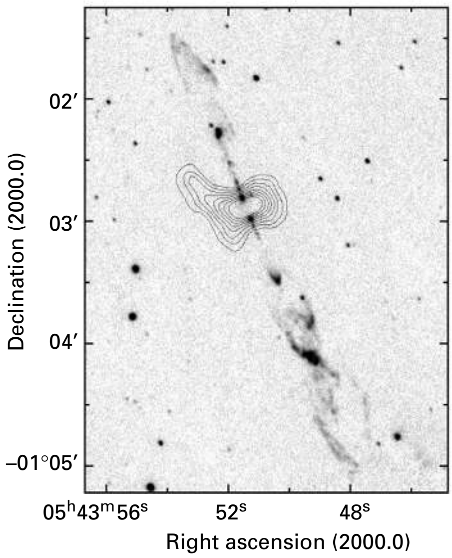


Fig. 1.3 The symmetric HH 212 outflow driven by twin jets from a concealed, centrally located protostar. It is located in the L 1630 molecular cloud about 90" north-east of the Horsehead nebula at a distance of ∼460 pc. The outflow is shown in emission from vibrating molecules of hydrogen ($H_2$ 1–0 S(1) at 2.12 μm). The contours correspond to emission levels from ammonia molecules (integrated $NH_3$ (1,1) emission at 23.7 GHz), produced from cold, dense gas. This molecular core harbours a protostar detected in the far-infrared. Credit: Wiseman *et al*. (2001), Calar Alto & Very Large Array (VLA). Reproduced by permission of the AAS.

up, i.e. the fluid follows divergent streamlines. Hence, they may well be associated with deceleration or instability. It still remains to draw a line between a collimated wind and a jet. For example, a length twice as long as the width sufficed in the past for a milli-arcsecond quasar feature to be described as a jet. These jets were observed with the continent-wide VLBI – the Very Large Baseline Interferometer. A minimum ratio of 4 has also been adopted by some astronomers.

The semantic distinction between jets and beams of plasma has changed through the years. Originally, jets were observed and beams were the hypothesised underlying flows. Common usage, however, has now evolved so that jets are both observed and theoretical. We will save the terms beam and beaming to refer to the relativistic effects caused by jet flows at speeds close to the speed of light. In this case, beaming refers to the anisotropic distribution of radiation that is produced in the reference frame of the central ejecting object. While necessary, these definitions may make better sense after we consider how the jet concept entered the daily working lives of many astrophysicists.

## 1.2 Jet presence and function

Our definition of a jet is not limited to those we can see: the energy-dissipating visible variety. In the past, even though the evidence for underlying jets has not always been compelling, the assertions have subsequently proved remarkably accurate.

There are strong reasons to believe that the production of jets is related to the efficient removal of angular momentum from accreting or collapsing systems. If they do their job efficiently, they allow almost all the spin to be extracted by ejecting a small fraction of the available mass. A high-performance jet would also be made to transport the energy a long distance with little loss on the way. Ironically, the best jets are then invisible. With no dissipation there is no radiation, and detection may then rely on reflection or absorption of external sources of light. In such cases, their presence can only be inferred.

On the other hand, there are reasons why jets could reveal their presence in all three fundamental flow phases. Firstly, at the point of launch, the driving mechanism is unlikely to be 100% efficient at converting energy into bulk flow. In the conversion process, some energy is dissipated into random particle motions which may lead to considerable radiative losses. Secondly, while propagating, velocity structure may grow within the jet flow. Velocity gradients tend to steepen into internal shock waves, and turbulence is generated by velocity shear or magnetic reconnection. Both shock waves and turbulence convert kinetic energy associated with coherent large-scale motions into thermal energy.

Finally, the interface with the ambient medium often provides indirect evidence and can be mistaken for the jet itself. For example, jets may excite a surrounding sheath of stationary gas or they may continuously supply an active region at the point of termination. This impact region is called a 'hot spot' in extragalactic terminology and a 'bow shock' in the star formation context (with those detected in optical light termed Herbig–Haro objects). Both are produced by shock waves which are by nature both dissipative and compressive; since radiation processes are sensitive to wave excitation and collision rates, these are ideal regions for strong emission.

An underlying jet may also be inferred from the detection of a few separated knots of emission which are well aligned. However, some evidence which suggests that they are being more or less continuously energised is required. This property distinguishes a jet flow from a ballistic flow of independent clumps of gas – the proposed 'plasmons' of radio galaxies and the 'bullets' of stellar jets.

The conclusion is that there are various conceivable efficiency coefficients for jets. We can define a transport efficiency in terms of the ability to transfer momentum or energy. We can define a propagation efficiency in terms of the ability to tunnel through the ambient medium. Finally, we can define a spin efficiency in terms of the fraction of the inflowing angular momentum which is extracted.

## 1.3 Early history

For centuries, jets of a kind have been discussed in astronomy. These had been observed from comets. Brilliant streams had been recorded, emanating from the nuclei of comets and undergoing sudden extensive changes. As far back as 1682, a distinctive curved jet appears in a drawing of Comet Halley by Hevelius (Hevelius, 1682). In 1836, Friedrich Bessel recorded 'out-streaming' from Comet Halley over arcs of 30–90°, rotating over hours and days on the sun-facing side (Bessel, 1836). He developed a theory to account for the brightness of the comet based on the evaporation from a solid nucleus. He realised that jets had an important consequence: a rocket effect. Material evaporated from the surface of the nucleus exposed to the Sun could provide the non-gravitational forces which alter the orbit of Comet Encke. A jet propulsion effect was thus thought to influence comet trajectories.

In 1881, Captain Noble remarked upon apparent spouting from the nucleus of Comet b, 1881 (Noble, 1881). In 1882, the rocket effect of a jet on this comet was discussed by C.E. Burton (Burton, 1882) as leading to non-gravitational disturbances. Specifically, he expected motion transverse to the orbit, rather than retardation or acceleration, to be detectable. In 1950, Whipple confirmed this with detailed calculations (Whipple, 1950) but the jet model was not developed. These days, jets are considered responsible for supplying the entire coma. They can be highly collimated, as we will discuss in Chapter 8. Only very recently, however, have we been able to approach comets and locate the source of the jets.

Meanwhile, in 1918, an extragalactic jet had been discovered by the astronomer Heber Doust Curtis at Lick Observatory (Curtis, 1918). It was reported as a 'curious straight ray'. As shown here in the later image of Fig. 1.4, it is 'apparently connected to the nucleus' of the nebula Messier 87 (M 87), also catalogued as NGC 4486. At that time, the nature of the ray as well as that of the nebula were unknown. With no basis, the phenomenon remained undiscussed for over forty years. Incidentally, Curtis had previously been aiding Wilson on recording the Halley jets (Wilson, 1910) but refrained from employing that description in his own work.

In 1954, Baade and Minkowski investigated the curious M 87 feature and renamed it as a 'jet' simply on a hunch that the feature could be part of a rapid outflow (Baade & Minkowski, 1954). They actually had some circumstantial evidence since, although the spectrum of the jet revealed a featureless blue continuum, an outflow had been associated with the innermost regions of the galaxy. The outflow was identified by a strong oxygen

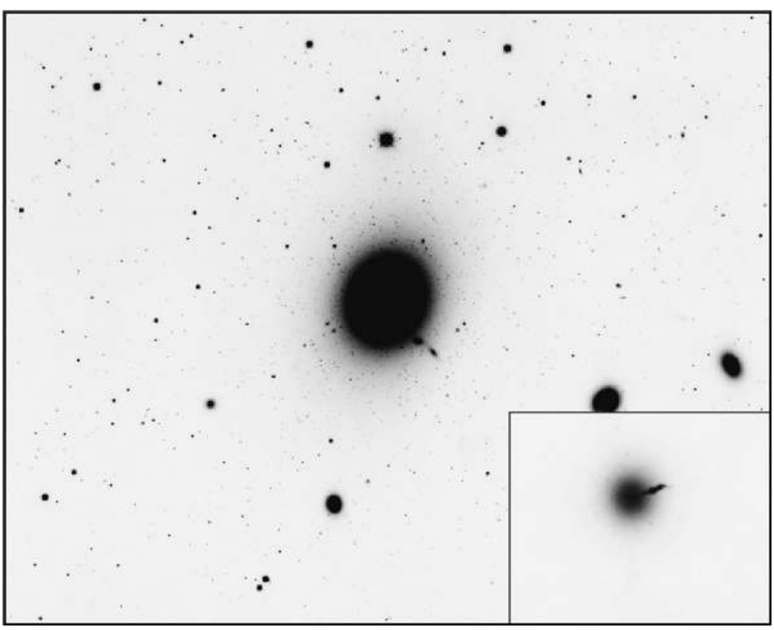

Fig. 1.4 The giant elliptical galaxy M 87 (type E0) in the Virgo Cluster at a distance of 16 Mpc, as imaged by the Kitt Peak 4-metre Mayall telescope in 1975. The image displays a 25" sub-cluster. The peculiar jet emanating from the core of M 87 is only visible in the processed image shown in the inset 1.4" panel. Credit: NOAO/AURA/NSF.

emission line, blue-shifted by 300 km $s^{-1}$ relative to the galaxy's nucleus. As it turns out, this is a thousand times slower than the jet as presently constrained.

Baade and Minkowski recognised that the jet could be just the visible apparition of a 'peculiar condition' extending over an enormous volume. This volume is occupied by material that generates radio emission. In fact, M 87 was associated with Virgo A, the third-strongest radio source in the northern sky. It was, hence, baptised as the Crab Nebula of Active Galaxies and it was reasonable to suppose that, like the amorphous Crab, the optical jet as well as the newly discovered radio galaxies were being observed through radiation produced by the synchrotron process (see § 1.6). Synchrotron radiation is emitted when a relativistic electron spirals around magnetic field lines. In 1955, Shklovskii made the critical prediction that the radiation should then be strongly polarised, which was soon verified by Baade (Baade, 1956).

As other jets were discovered in radio galaxies and quasars, such as 3C273, 3C48, 3C 196 and 3C 279, the M 87 jet became the classical example of the phenomenon, being so nearby and bright. Quite peculiar was that these first jets were all one-sided, whereas almost all radio sources were double. A second early problem was that the relativistic electrons should lose their energy well before propagating down the jet from the nucleus. Hence, the jets should not remain visible for such lengths (Shklovskii, 1963).

The discovery of the powerful extragalactic radio sources led to the need for an energy supply, which had to lie in the quasar or galactic nucleus. The typical radio source consists of two lobes symmetrically located about a central galaxy (seen at optical wavelengths). After the identification of many radio sources with galaxies in 1949, the first radio galaxy found to be bisected was Cygnus A in 1954. After this, the third Cambridge (3C) catalogue, released in 1959, contained images of many of the brightest radio sources and established prototypes for many of the categories now used as household names by jet enthusiasts. Subsequently, various catalogues and classes of radio sources, associated with jets launched from diverse types of galactic nuclei, have been discovered. These will be explored in Chapters 4 and 5.

The idea that the supply might be continuous from within a parsec out to hundreds of kiloparsecs was not quick to emerge. Jets were rarely detected and twin jets not at all envisaged. Therefore, interpretations in terms of non-continuous ejections were favoured. Scenarios in which clouds of plasma, later packaged as 'plasmons', were somehow breaking out along an axis of least resistance (Shklovskii, 1963), were developed. A gravitational slingshot mechanism was also proposed (Saslaw *et al.*, 1974). The advantages of expelling relativistic gas and magnetic field in clouds later called 'plasmoids' (Christiansen *et al.*, 1978) had also been noted by Rees (Rees, 1966).

This all began to change in 1971, when Rees proposed a 'black box' model in which the black box is situated at the centre of certain galaxies, somehow channelling energy into the radio lobes (Rees, 1971). He actually proposed that the energy was transmitted through a tube in the form of a beam of low-frequency radiation. The beam was replaced by a gas jet in 1974 and methods employed in classical fluid dynamics were adapted to the expected environments of galactic cores (Blandford & Rees, 1974). Finally, astronomers were able to detect the jets themselves at radio wavelengths, and some were indeed found to belong to oppositely directed pairs. One of the most stunning early examples was associated with NGC 6251 (Fig. 1.5). The generation of a jet from a blowtorch-like flame within one parsec of the nucleus, yet extending out over 100 000 parsecs without a significant alteration in

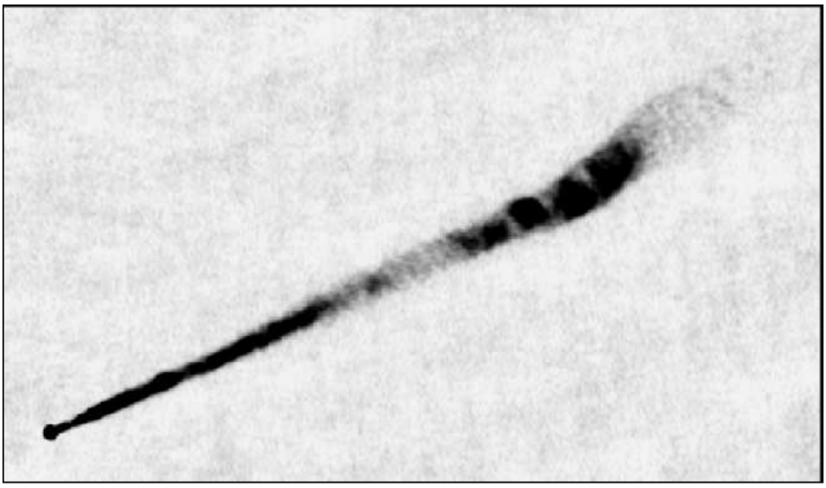

Fig. 1.5 A radio image of the jet associated with the galaxy NGC 6251 taken at 1.4 GHz with the Very Large Array in New Mexico. At a distance of 107 Mpc, the jet extends 140 kpc (280") on this image. The host galaxy is located at the eastern (left) end of the jet. A very faint counterjet has been detected. Credit: NRAO & Werner *et al*. (2001).

direction, is a phenomenal achievement for a natural process. And so, astrophysical jets became an important field of research in astronomy.

The discovery of motions faster than the speed of light within a jet was to radically alter our approach. In 1979, it was reported that features in the 3C 279 jet that were followed over a period of years moved at ten times the speed of light (Whitney *et al*., 1971), seemingly impossible until one distinguishes between apparent motion and intrinsic motion. Such superluminal motion was subsequently measured in other quasar jets, requiring an explanation to be found that could be lent to the entire class.

## 1.4 Surprising discoveries

The discovery that young stars could also drive jets followed a similar trail. Again in the 1950s, small 'clots' of optical emission were detected, sometimes aligned or in groups. Being found in dark clouds and regions containing young stars called T Tauri stars, they were immediately associated with the birth of stars (Herbig, 1951; Haro, 1952). The class of clots was soon named Herbig–Haro objects after their initial finders.

At first, the objects were interpreted as protostars and reflection nebulae. However, spectroscopy revealed atomic emission lines which were specifically attributable to shock waves, i.e. regions of impact. What was the catalyst for the impacts? Once more, in the absence of jets, plasmons were invoked, this time in the form of interstellar bullets (Norman & Silk, 1979)

The early 1980s brought new technologies which led towards another explanation. First, bipolar outflows were discovered, often associated with the Herbig–Haro objects (Bally & Lada, 1983). These were wide lobes containing large masses of cold molecular gas moving at supersonic speeds (deduced from submillimetre emission lines produced by molecules of carbon monoxide when excited into rotation). Two lobes were often apparent, straddling a molecular core, with some mirror symmetry somewhat akin to radio galaxy structure. Unlike their cousins, however, the speed of the outflows could be deduced from the molecular lines. It was found that the lobes possessed distinct radial velocities, blue- and red-shifted relative to the central core. This narrowed down the options – the lobes had to be somehow driven by a centrally located, very young star.

Confirmation that jets were present came when, one after another, optical jets, the atomic blowtorches, were revealed on deep CCD images. The first structure, HH 47 in the Gum nebula, was interpreted as a streamer being excited by a jet (Dopita *et al*., 1982). The optical jets seemed rather inconsequential, carrying low power and feeding Herbig–Haro objects which speed away and disappear into the interstellar medium. Their potential importance to star formation was not fully recognised until the 1990s when jets from protostars were also discovered. The 'most beautiful' twin jets, displayed in Fig. 1.3, were given the appropriately symmetric name HH 212. The HH 212 outflow demonstrates how jets have helped us discover and then locate new protostars.

Meanwhile, in 1980, the discovery of one apparently unique outflow eclipsed all others. A pair of jets were found to emanate from near the centre of a supernova remnant called W 50 about 4.5 pc away, lying in the constellation of Aquila. The jet source was SS 433, an eclipsing binary system with a 13.1 day period. It was the first evolved stellar system (i.e. one which has finished its main period of hydrogen fusion) to display jets. Two oppositely directed jets were found, with material moving ballistically at a speed of $\sim 0.26\,c$, over a quarter of the speed of light. The jets slowly precess over a wide angle as deduced from 'bizarre' moving atomic emission lines (i.e. shifting Doppler shifts) brought to our attention by Margon *et al*. (1979). We now include SS 433 as a member of a class of high-mass X-ray binaries with one component an accreting neutron star and the companion an early-type star undergoing high mass loss. While a few other compact stellar objects in binary systems, including white dwarfs and black holes, have since been added to the jet list, no object has made such an impact as SS 433.

Microquasar is the term now used to describe a particular class of evolved stars which grew in membership in the 1990s (Mirabel & Rodríguez, 1994). These are radio-emitting X-ray binaries, scaled-down versions of quasars with a radio morphology like quasars and high X-ray luminosity. They are powered by black holes or neutron stars which accrete as part of a binary system. The first star-like object to display jets that exhibit relativistic motion was SS 433. Famous objects in this class are Scorpius X-1 (the first known extrasolar X-ray source) and Cygnus X-1 (the first strong black hole candidate). In these cases, the black hole is only a few solar masses and the accretion disc is hot, generating strong X-ray emission. In a number of associated jets, the motion is superluminal. As a result, by following their temporal behaviour over days, we are now able to explore relativistic twin jets in detail (Rodríguez & Mirabel, 1999).

A more recent addition to the jet-nurturing family is an entire class of planetary nebula (PN). As a star of intermediate mass enters the end stage of its life, the red giant or supergiant phase, winds or weakly collimated outflows appear. These so-called bipolar nebulae are not to be confused with bipolar outflows associated with young stars. These structures have long been known and lend planetary nebula their often spectacular mirror symmetry. Their cause is not entirely due to jets, but the interaction of jets with winds turns out to be vital to their structure. A massive, low-velocity wind removes a large fraction of the material during the asymptotic giant branch (AGB) phase and is followed by a higher-velocity, lower-mass wind that snowploughs into the previously ejected material (post-AGB phase). However, in addition to the global structure, fine structure such as knots and jets is found in about half of PN. In this case the knots are called FLIERS (fast low-ionisation emission regions). Although they are seen on opposite sides of the central star along the major axis of elliptical planetary nebulae, there is no substantial evidence that they are driven by jets.

The discovery of bona fide planetary nebula jets goes back to 1985 when Gieseking *et al*. (1985) and Feibelman (1985) found jet-like features (both through imaging and by spectroscopy). The first twin-jet was found to emanate from the star driving the Eskimo nebula (NGC 2392), while the existence of the one-sided jet in Henize 2-36 (He 2-36) has been controversial. Since then, numerous jets have been discovered in the transition stage (proto-planetary nebula) as well as in the PN stage.

Moving into the 1990s, supernovae have provided us with new hosts for jets. The original feature labelled as the Crab Nebula jet (van den Bergh, 1970), however, is non-radial and is probably a fast-moving filament rather than a true jet in the sense discussed here. Still, jets of relativistic particles were suspected to be driven from pulsars, i.e. the rapidly-rotating neutron stars left over from the explosions (Weiler & Sramek, 1988). The ROSAT X-ray telescope finally revealed extended jets from within the Pulsar Wind Nebula associated with the Crab and Vela pulsars. These jets emit synchrotron radiation from relativistic electrons or positrons. Since then, the Chandra X-ray satellite has revealed a few other pulsar jets, suggesting the existence of a new class with fascinating properties.

Gamma-ray bursts (GRBs) are short-lived bursts of gamma-ray photons, the most energetic form of light. Their serendipitous discovery by US military satellites actually goes back to the late 1960s (Klebesadel *et al*., 1973). However, the cause of the bursts and the central role played by jets were only realised at the turn of the century. Long-duration bursts that last anywhere from two seconds to a few hundreds of seconds are plausibly associated with hypernovae and collapsars in distant galaxies, collapsars being black holes which mark the death of especially massive stars. With the event, a jet of matter at an ultra-relativistic velocity is ejected. The GRB itself and the afterglow at longer wavelengths are from the jet. The anisotropic emission from a beamed relativistic jet remains at a very low level until the Doppler cone of the beam intersects the observer's line of sight, making off-axis GRB jets directly detectable only at long wavelengths and late times (exceeding one year). Convincing evidence that jets are involved was perhaps first presented by analysing GRB 990123, where a predicted break in the light curve was observed. Since GRBs are now detected roughly once per day from random directions of the sky, we have access to a remarkable sample of relativistic jets.

## 1.5 Overview and points of view

Bringing all astronomical jets under one umbrella is not facilitated by the physics. There are no physical mechanisms or radiation processes to unify a discussion. The flowing material and emitted radiation cover almost every astrophysical possibility. This is because jets stem from a diverse range of objects (Table 1.1) and are launched through a broad range of environments. The variety is no better demonstrated than by comparing their sizes and speeds, as listed in Table 1.2. Their timescales are also simply incomparable. This means that we will need to take a broad sweep of relevant astrophysical radiation and flow processes before we can get familiar with the jet families.