X-ray jets from active galactic nuclei

Introduction

Active galactic nuclei (AGN) are supermassive black holes which form the centres of galaxies, and emit large amounts of energy in radiation and particle flows. One feature of many AGN are jetted outflows, which can be observed through radio emission, and sometimes also in other parts of the electromagnetic spectrum, including x-rays. These jets are large flows of plasma at relativistic speeds, over lengths of order 10^{20} m, which is tens of thousands of light years. The x-ray emission from jets is usually dominated by synchrotron emission from relativistic electrons gyrating in the magnetic field of the jet.

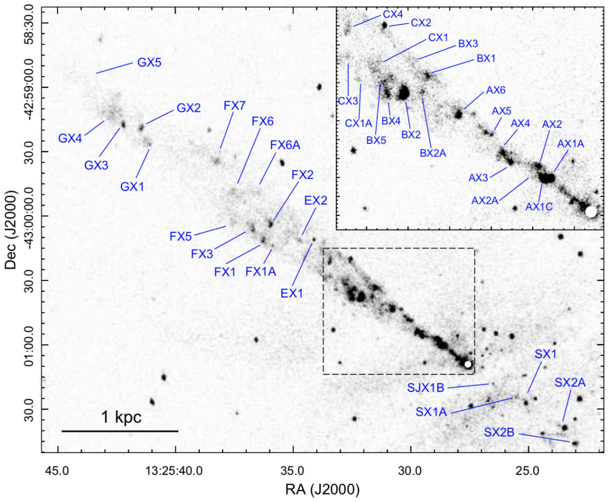

Figure 1: X-ray image of the jet from the Centaurus A AGN. Darker regions represent regions of higher intensity x-rays. Brighter regions within the fainter jet are called knots. (Snios *et al.*, 2019)

Part A: 1D fluid model of a jet

A simple model of the flow of jets assumes that the flow is steady and directed radially away from the central AGN, so approximately one dimensional, and that the plasma in the jet is in pressure equilibrium with its surroundings. There is assumed to be a constant rate per volume of mass injected into the jet from stars which lose their outer layers as they move through their life cycle.

The jet is described in terms of the coordinate representing distance from the AGN, s, and the opening radius r of the conical jet. These distances are measured in parsecs, where $1\ \mathrm{pc} = 3.086 \times 10^{16}\ \mathrm{m}$. The speed of the jet flow is assumed to be directed radially away from the central AGN, and be a function of s only. The plasma in the jet is comprised of electrons, protons, and some heavier ionised nuclei. The average energy carried by each particle in the jet, in the reference frame of the bulk flow of the jet (which we will call the jet frame), is $\epsilon_{\mathrm{av}} = \mu_{\mathrm{pp}}c^2 + h$, where the term h includes all thermal kinetic energy and potential energies in terms of the pressure P and n is the number density of the plasma.

As the stars, which the jet flows past, move through their life cycles they can lose part of their atmosphere. This results in a uniform rate of injection of mass per unit volume α into the jet, and the injected particles are assumed to be at rest relative to the AGN.

This model can be applied to the Centaurus A jet. Centaurus A is one of the nearest AGN, so it is possible to observe its jet at relatively high spatial resolution. The total power carried by the jet is estimated to be $P_\mathrm{j} = 1 \times 10^{36}$ J.s^{-1}. See below for a diagram of a simple geometrical description of the Centaurus A jet, including measurements of some jet parameters. s_1 is the coordinate of the start of the jet, and s_2 the coordinate of the end of the jet. In Centuarus A the average mass per particle is $\mu_\mathrm{pp} = 0.59 m_\mathrm{p}$ and $h = \frac{13}{4} P/n$ .The pressure in the plasma surrounding the jet is $P(s) = 5.7 \times 10^{-12} \left(\frac{s}{s_0}\right)^{-1.5}$ Pa, where $s_0 = 1\ \mathrm{kpc}$.

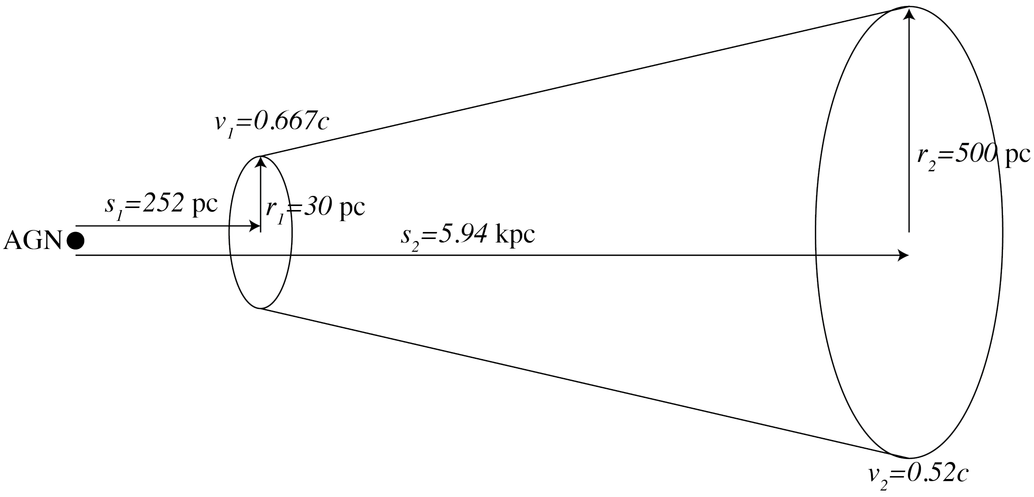

Figure 2: The Centaurus A jet, showing the geometry compared to the active galactic nucleus (AGN).

The jet is described by the following parameters, all of which depend on the distance s from the AGN:

- the opening radius of the jet $r(s)$ in the AGN frame
- the cross sectional area of the jet $A(s)$ in the AGN frame
- the speed of the jet $v(s)$ in the AGN frame
- the lorentz gamma factor of the jet $\gamma(s)$ in the AGN frame
- the number density $n(s)$ in the frame of the jet

Any of these parameters can be used in your answers to A1-4.

A.1 Find the number density of particles, $n'(s)$, in the frame of the AGN, in terms of the proper number density, $n(s)$ and other jet parameters. The proper number density is the number density in the frame which is locally co-moving with the jet plasma outflow, which we will call the jet frame. 0.3pt

A.2 Find the flux of particles, $F_p(s)$, across a cross section of the jet with area A, at a distance s from the AGN. 0.2pt

A.3 Write a continuity relationship between the particle flux into the jet and out of the jet in terms of the jet parameters at s_1 and s_2, and V, the total volume of the Centaurus A jet and other required parameters. 0.5pt

A.4 Write a relationship between the energy flux into the jet, and the energy flux out of the jet in terms of the jet speeds, cross sectional areas and proper number densities at s_1 and s_2, the volume, V, of the jet and any other required parameters of the Centaurus A jet. 0.6pt

The power carried by a jet is defined to be the sum of the total bulk kinetic energy flux and the total thermal energy flux, so

$$P_{\mathrm{j}}(s) = F_{\mathrm{E}}(s) - \dot{M}c^2 \tag{1}$$

where $F_{\mathrm{E}}(s)$ is the flux of energy through the cross section of the jet at s, and $\dot{M}$ is the mass flux through the jet cross section at the same distance s from the AGN.

A.5 Using your answers to previous parts find $\frac{dP_{\mathrm{j}}}{ds}$. 0.6pt

A.6 Find numerical values for the mass fluxes $\dot{M}_1$, into the Centaurus A jet at s_1, and also $\dot{M}_2$, out of the Centaurus A jet at s_2, 0.4pt

A.7 Find an expression for the total momentum flux, Π, into the Centaurus A jet. Also numerically evaluate this expression. 0.5pt

A.8 Find a numerical value for the total force due to external pressure, F_{Pr}, on the Centaurus A jet. 0.5pt

A.9 Write the expected relationship between Π and F_{Pr}. Also, calculate the percentage difference between the model value of Π , which you found in A7, and the expected value. 0.2pt

Part B: Gas of ultra relativistic electrons

Consider a gas of ultra relativistic electrons ($\gamma \gg 1$), with an isotropic distribution of velocities (does not depend on direction). The proper number density of particles with energies between ϵ and $\epsilon + d\epsilon$ is given by $f(\epsilon)d\epsilon$, where ϵ is the energy per particle. Consider also a wall of area ΔA, which is in contact with the gas.

B.1 Write an integral expression for the total energy per volume of the electron gas. 0.2pt

B.2 Find an expression for the total rate of change in momentum $\Delta p_z/\Delta t$ of the gas, in the z-direction which is normal to the wall, due to collisions with the wall. 0.8pt

B.3 Derive an equation of state for an ultra relativistic electron gas, relating the pressure, volume and total internal energy. 0.6pt

B.4 Derive a relationship between the pressure and volume of an ultra relativistic electron gas undergoing an adiabatic expansion. 0.6pt

Part C: Synchrotron emission

In the jets from AGN, we have populations of highly energetic electrons in regions with strong magnetic fields. This creates the conditions for the emission of high fluxes of synchrotron radiation. The electrons are often so highly energetic, that they can be described as ultra relativistic with $\gamma \gg 1$.

C.1 Find an expression for Ω, the angular frequency of gyration of an electron with lorentz factor γ and travelling at an angle ϕ to the magnetic field B. 0.7pt

As the electron is accelerated due to the magnetic field it emits electromagnetic radiation. In a frame at which the electron is momentarily at rest, there is no preferred direction for the emission of the radiation. Half is emitted in the forward direction, and half in the backward direction. However, in the frame of the observer, for an electron moving at an ultra relativistic speed, with $\gamma \gg 1$, the radiation is concentrated in a forward cone with $\theta \lesssim 1/\gamma$ (so the total angle of cone is $2/\gamma$). As the electron is gyrating around the magnetic field, any observer will only see pulses of radiation as the forward cone sweeps through the line of sight.

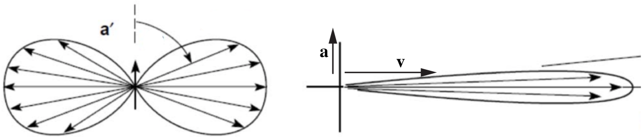

Figure 3: The diagram on the left shows the distribution of power in radiation from an electron accelerating up the page in the frame at which the electron in momentarily at rest. The diagram on the right shows the distribution of power in radiation for the same electron in the observer's frame, where most radiation is emitted in the forward cone. In the observers frame, the direction of the electron's acceleration is shown by a vector labelled **a** and the direction of its velocity is shown by a vector labelled **v**.

C.2 Find the duration of a pulse, Δt, of synchrotron radiation observed from an electron with lorentz factor γ, travelling at an angle ϕ to the magnetic field. 0.5pt

C.3 Hence, estimate the characteristic frequency, ν_{chr}, of the synchrotron radiation. 0.3pt

The total synchrotron power emitted is

$$P_{\mathrm{s}} = \frac{1}{6\pi\varepsilon_0}\left(\frac{q^4 B^2 \sin^2\phi}{m^4 c^5}\right) E^2 \tag{2}$$

C.4 Estimate the time, τ, for an electron of energy E to lose its energy through synchrotron cooling. 0.2pt

Part D: Synchrotron emission from an AGN jet

The distribution of electron energies in a jet from an AGN is typically a power law, of the form $f(\epsilon) = \kappa\epsilon^{-p}$, where $f(\epsilon)d\epsilon$ is the number density of particles with energies between ϵ and $\epsilon + d\epsilon$. The corresponding spectrum of synchrotron emission depends on the electron energy distribution, rather than the spectrum for an individual electron. This spectrum is

$$j(\nu)d\nu \propto B^{(1+p)/2}\nu^{(1-p)/2}d\nu \quad . \tag{3}$$

Here $j(\nu)d\nu$ is the energy per unit volume emitted as photons with frequencies between ν and $\nu + d\nu$

Observations of the Centaurus A jet, and other jets, show a knotty structure, with compact regions of brighter emission called knots. Observations of these knots at different times have shown both motion and brightness changes for some knots. Two possible mechanisms for the reductions in brightness are adiabatic expansion of the gas in the knot, and synchrotron cooling of electrons in the gas in knot.

The magnetic field in the plasma in the jets is assumed to be *frozen in.* Considering an arbitrary volume of plasma, the magnetic flux through the surface bounding it must remain constant, even as the volume containing the plasma changes shape and size.

D.1	For a spherical knot which expands uniformly in all directions from a volume of V_0 to a volume V, with an initial uniform magnetic field B_0 Find the magnetic field B in the expanded knot.	0.4pt

D.2	Find $f(\epsilon)$, the distribution of electron energies after adiabatic expansion of a spherical knot to a volume V on the distribution of electron energy densities, given that the knot of volume V_0 has an initial distribution of electrons $f_0(\epsilon) = \kappa_0\epsilon^{-p}$, where $f_0(\epsilon)d\epsilon$is the number density of particles with energies between $\epsilon$and $\epsilon + d\epsilon$.	1.0pt

D.3	How will synchrotron cooling affect the distribution of the electrons? After a time interval where electrons have been undergoing synchrotron cooling, will the distribution of electron energies as a function of ϵ be steeper, shallower or leave it unchanged. Justify your answer with equations, by considering two electron energies $\epsilon_1 < \epsilon_2$.	0.3pt

The table below summarises some observations of knots (brighter regions) in jets from two AGN, Centaurus A (Cen A) and M87.

AGN	Time between observations	Knot	Brightness change in x-rays	Spectral changes in x-rays	Brightness changes in other bands (e.g. UV, optical)
Cen A	15 years	AX1C	-23%	No change	No data
Cen A	15 years	BX2	-15%	No change	No data
M87	5 years	HST-1	-73%	No data	No change
M87	5 years	Knot A	-12%	No data	No change

(Data from Snios et *al.*, 2019a; 2019b.)

D.4 In the table in the answer sheet, identify the more likely cause of reduced brightness for each knot, and identify which previous part or parts support your conclusion. 0.6pt