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M.Phys. & M.Math.Phys.

High-Energy Astrophysics

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High-Energy Astrophysics: Synopsis

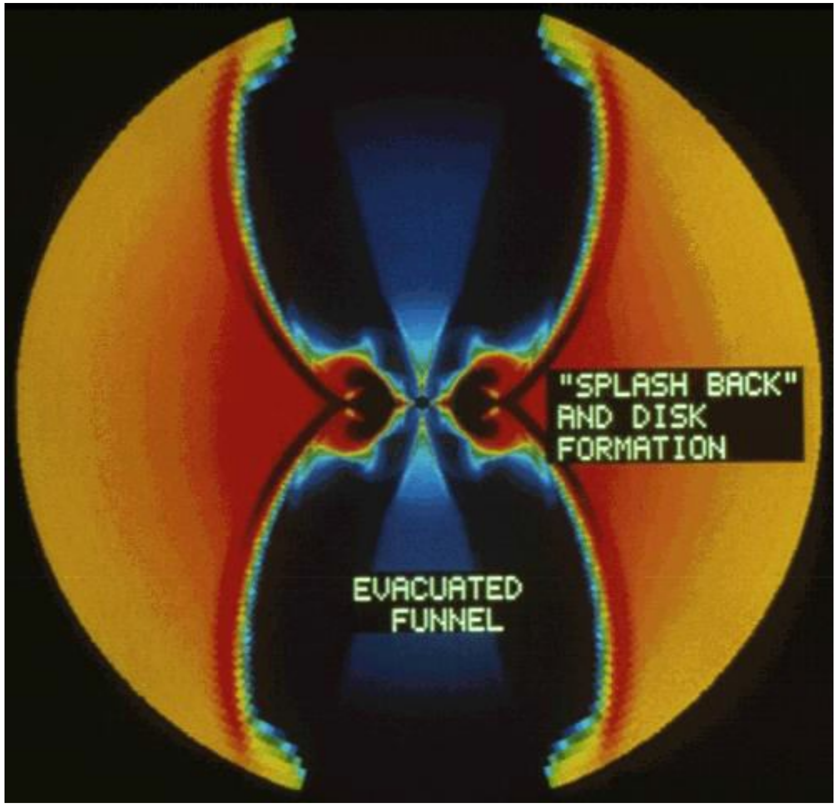
1) Supernova blast waves; shocks.
2) Acceleration of particles to ultra-relativistic energies.
3) Synchrotron emission; total power and spectrum
4) Synchrotron self-absorption, population ageing, radio galaxies.
5) Accretion discs: structures and luminosities.
6) Accretion discs: spectra, evidence for black holes.
7) Relativistic jets; relativistic projection effects; Doppler boosting.
8) Cosmic evolution of AGN; high-energy background radiation and cosmic accretion history of black holes.
9) Bremsstrahlung; inverse-Compton scattering; clusters of galaxies; Sunyaev-Zel’dovich effect.
10) Cosmic rays and very-high-energy gamma rays; Cherenkov telescopes.

Models for jet production

We are now near the boundaries of our understanding of AGN and stellar-mass jet-producing engines. The very central question still remains unanswered: just how is the jet created in the first place?

Jet production I: pure radiation pressure?

- Geometrically thick accretion disc disc as “funnel”.
- A bloated inner accretion disc would have extremely high radiation density at its centre. This would provide a poorly collimated but powerful outflow. Then *reconfinement shock* creates collimated jet
- Detailed shape of nozzle requires full GR calculation; questions about stability, efficiency. How sure are we of bloated disc?
- Creating the jet as a positron/electron plasma by pair production has problems: *Compton drag* – i.e., the electrons and positrons scattering against the radiation field - would quench a powerful jet close to the black hole.

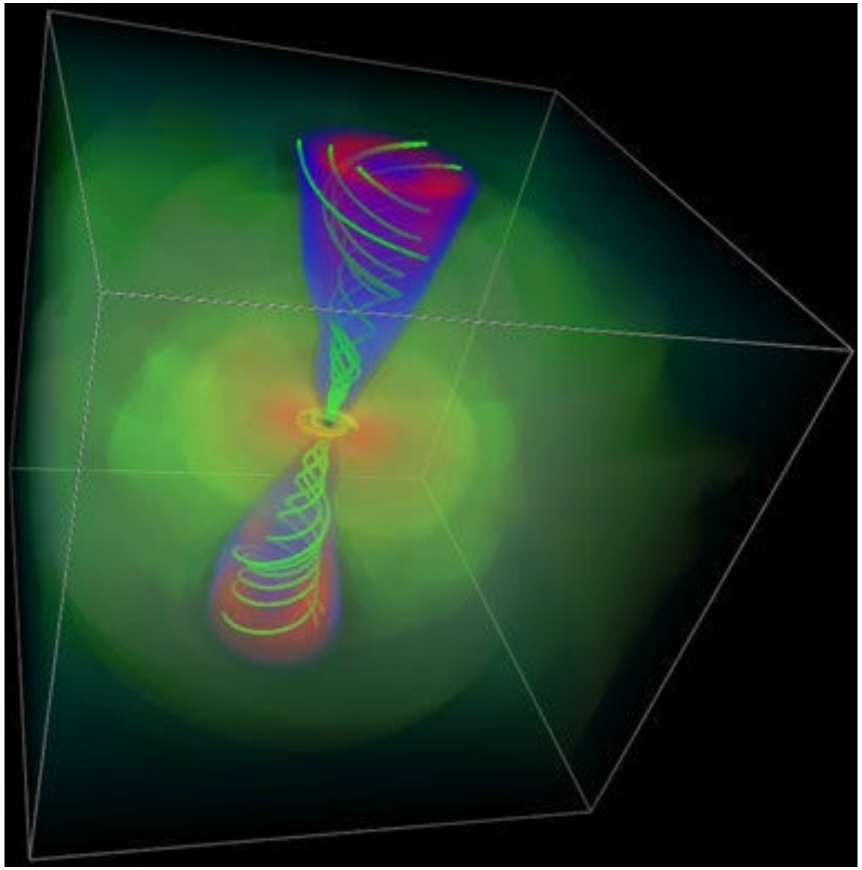


Numerical simulation of jet-producing “funnel” at the centre of a thick accretion disc.

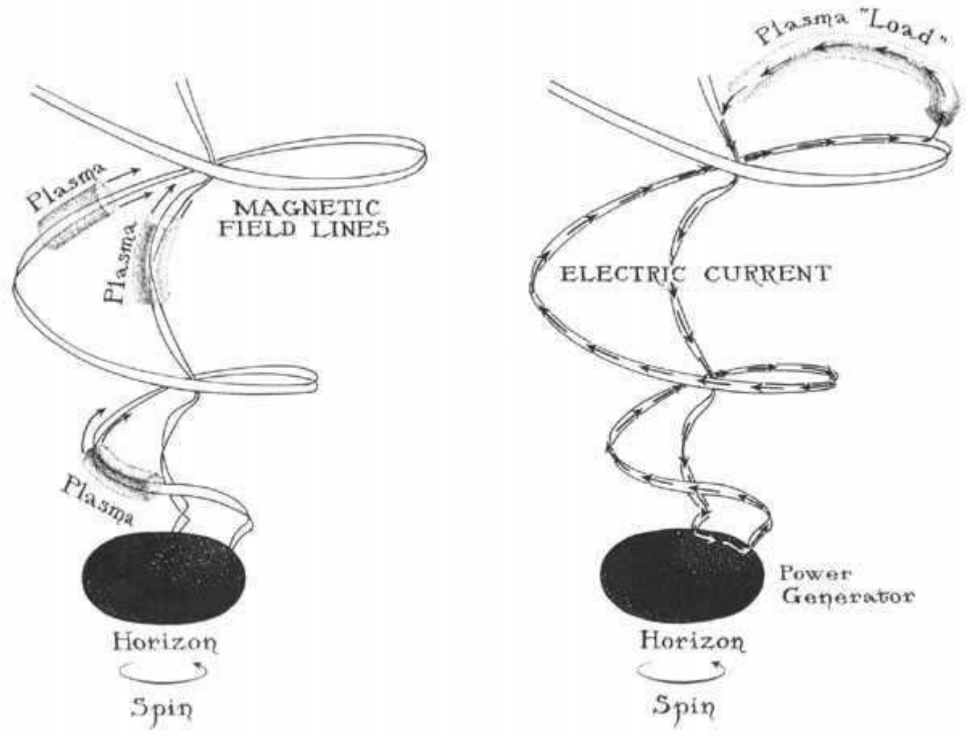
Jet production II: Magnetic Fields

- A toroidal **B** is a natural mechanism to collimate the jet.
- It is possible to extract energy from the black hole: it can *conduct* and so can produce a dynamo effect.
- Whatever the exact manifestation we know that **B** fields must likely be strong near to SMBH because infalling material has carried and compressed **B** from the ISM of the host galaxy.
- Mechanism needs a thin disc.

McKinney & Blandford GRMHD simulation



Magnetic fields: The Blandford-Znajek mechanism



Black hole horizon has resistance of empty space (377 Ω)!

Current passing through circuit is

$$I = \frac{\int \mathbf{v} \times \mathbf{B} \cdot \mathrm{dl}}{R_H + R_L}$$

Order of magnitude: maximally rotating Kerr hole, set $R_H \sim R_L$, set B energy density near hole similar to gas pressure near hole. Power $I^2 R$ works out to be:

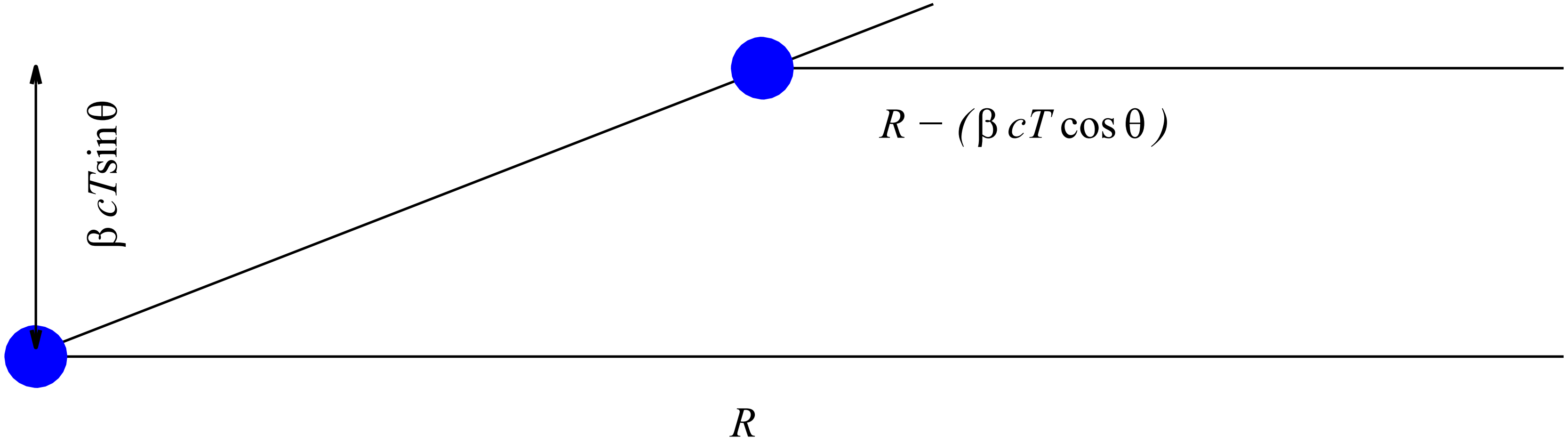
$$P \sim 10^{38} \frac{M_{\mathrm{BH}}}{10^9 M_\odot} \mathrm{W}$$

Which is available to accelerate particles away from the black hole.

Superluminal motion

The existence of jets in AGN means that spherical symmetry is broken. But we cannot take an individual active galaxy and rotate it to see what it looks like from a different angle. Hence a large amount of effort has been devoted to making statistical inferences about different types of AGN, and detailed observations of observational effects which should be orientation dependent. The underlying motive is, of course, to make as simple a model as possible, in which many of the observationally diverse types of AGN are the same type of beast, just viewed from a different position.

The most spectacular of these was proposed theoretically in the early days of AGN studies by Martin Rees, and with modern techniques it can be readily observed in many quasars with bright jets: *superluminal motion*.


$\beta\, cT \sin\theta$
$R - (\beta\, cT \cos\theta)$
R

Superluminal motion: calculation

In this calculation we will assume that the quasar and observer are at rest w.r.t. each other in flat spacetime. A full calculation including cosmological terms masks the intrinsic physics here (and, indeed, we now know of superluminal microquasars within the Galaxy, for which this treatment is exact).

Let us assume that a quasar lies at a large distance R from the observer, and its jet is inclined to the line-of-sight at an angle θ. Suppose a "blob" of bright emission in the jet—say a shock travelling up the jet— leaves the nucleus and and travels up the jet at speed βc.

The observer sees the blob leave the nucleus at time

$$t_1 = \frac{R}{c}$$

Now let the blob propagate up the jet for some time T in the frame of the nucleus. After this time, the blob has a *transverse* separation

$$\Delta X = \beta c T \sin\theta$$

Remember the observer can only measure the component of separation in the plane of the sky.

Superluminal motion: calculation contd.

Now consider the time at which the observer *sees* the blob reaching this distance from the nucleus. The light is emitted at time T but only has to travel a distance $R - \beta c T \cos\theta$. So the observer sees the blob reach position ΔX at time

$$t_2 = \frac{R}{c} + T(1 - \beta\cos\theta)$$

Hence the apparent transverse velocity is

$$\begin{aligned}\beta_{\mathrm{app}} c &= \frac{\Delta X}{t_2 - t_1} \\ &= \frac{\beta c \sin\theta}{1 - \beta\cos\theta}\end{aligned}$$

So for β close to 1 and small θ, we can easily observe $\beta_{\mathrm{app}} > 1$. Values of β_{app} up to $\sim$ 5—10 are measured.


Mauna Kea
Hawaii
Owens Valley
California
Brewster
Washington
North Liberty
Iowa
Hancock
New Hampshire
Kitt Peak
Arizona
Pie Town
New Mexico
Fort Davis
Texas
Los Alamos
New Mexico
St. Croix
Virgin Islands

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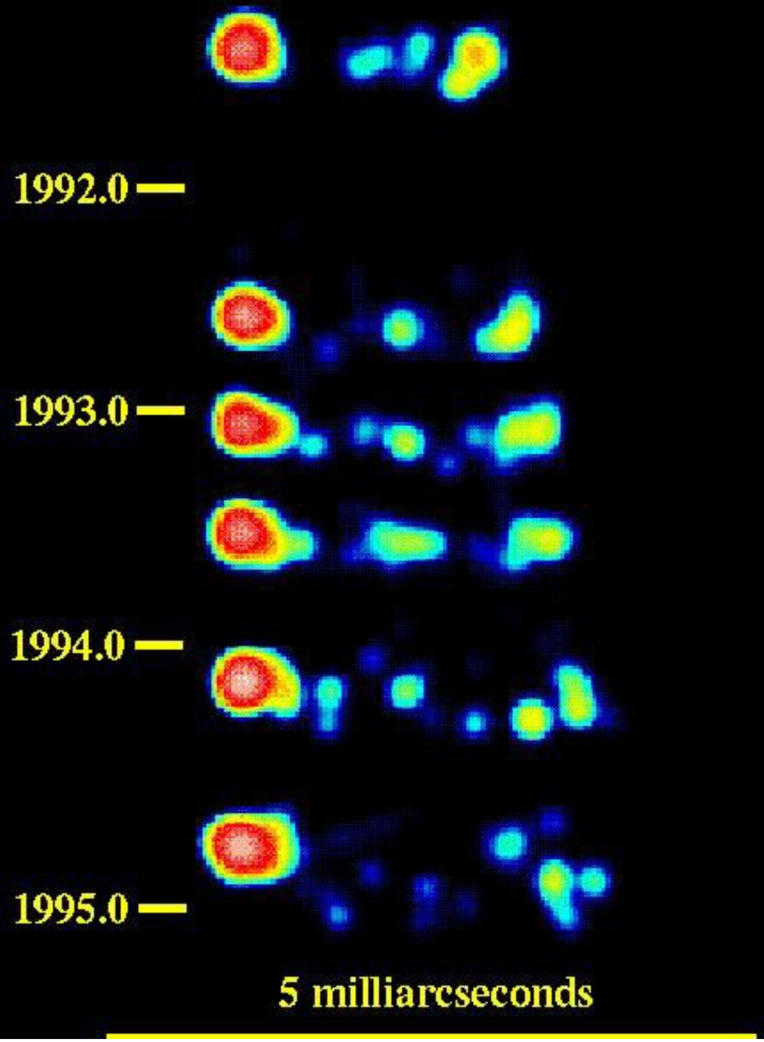
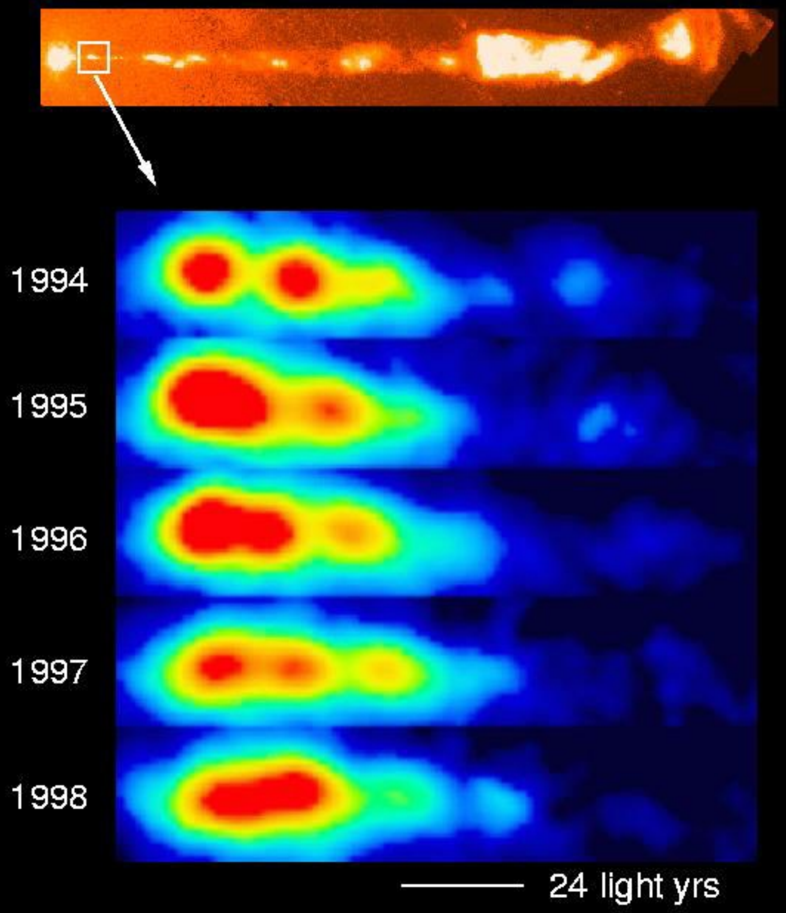
Superluminal Motion



Superluminal Motion in the M87 Jet



Superluminal motion: population statistics.

The *maximum* value of β_{app} which can be produced by a jet arises when $\beta = \cos\theta$, for which...

$$\beta_{app} = \gamma\beta$$

...the proof of which is on the next question sheet.

By taking the upper limit of β_{app} in large samples of quasars, we infer that the bulk motion in the jets typically has $\gamma \dashleftarrow 5$ to 10.

The *distribution* of β_{app} in the quasar population can then be used to infer their distribution in line-of-sight angle. We find that quasar jets are not isotropically distributed in angle: they preferentially point towards us. More on this shortly.

Caveats for superluminal motion measurements. . .

- How certain are we that one component is being followed?

- Is the “core” really the core—self absorption varies with observing frequency and the measured “central” component not necessarily be the very centre of the core.

- How to deal with accelerating/decelerating blobs?

Doppler boosting of relativistic jets

The radiation emitted by a blob of jet material will be relativistically Doppler boosted towards (or away from) the observer. Here we shall calculate how the effects the observed *brightness* of the jet.

First we recall the Doppler Factor for radiation emitted by a source moving at an angle θ to the line of sight:

$$D = \frac{1}{\gamma(1 - \beta \cos\theta)}$$

where γ is the usual Lorentz factor and $\beta = v/c$. Photons are received in the observed frame at a rate D times the rate they are emitted. To calculate the brightness in the observed frame, we must consider two other factors.

Doppler boosting of relativistic jets contd.

First, the solid angle subtended in the observed and emitted frames is different; the emitted radiation is preferentially beamed towards the direction of motion. Angle transforms as

$$\mathrm{sin}\theta' = D\mathrm{sin}\theta$$

and so solid angle transforms as

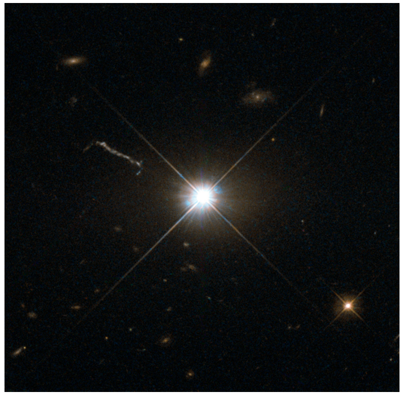
$$\mathrm{d}\Omega' = D^2\mathrm{d}\Omega$$

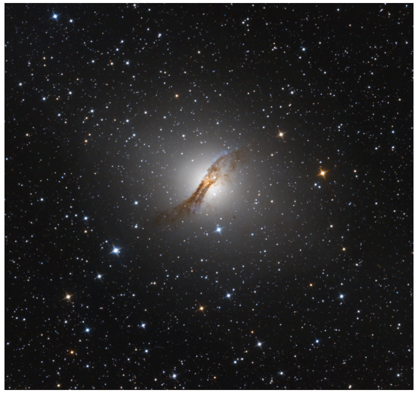
Second, photons received at some particular energy in the observed frame will have been emitted at a different energy. Using our parametrisation of the spectrum $S_\nu \propto \nu^{-\alpha}$, we find that the total observed brightness for a source varies as

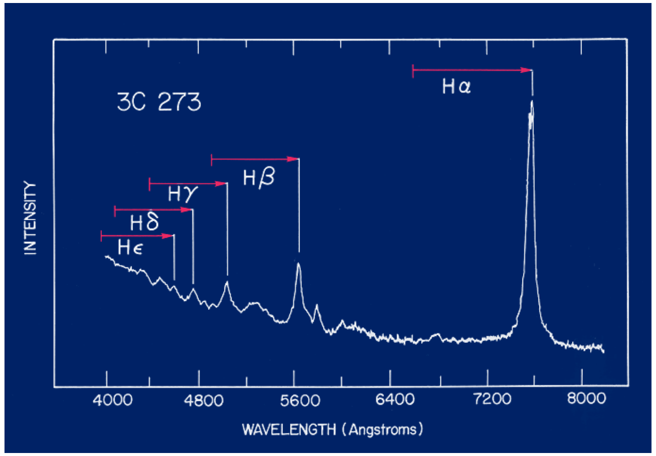
$$B_{\mathrm{obs}} = B_{\mathrm{em}} D^{3+\alpha}$$

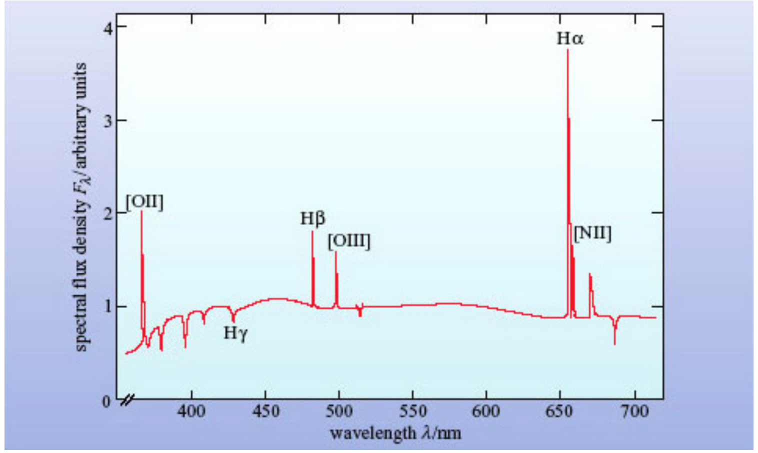
N.B. the emission from a blob approaching us is Doppler boosted and the brightness is *increased*; a receding blob has its emission Doppler boosted away from us and its brightness is *decreased* by this factor.

Quasar vs Radiogalaxy in the optical



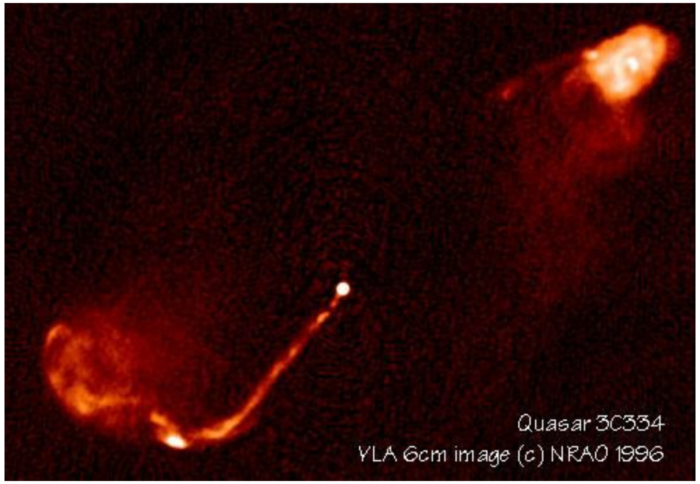


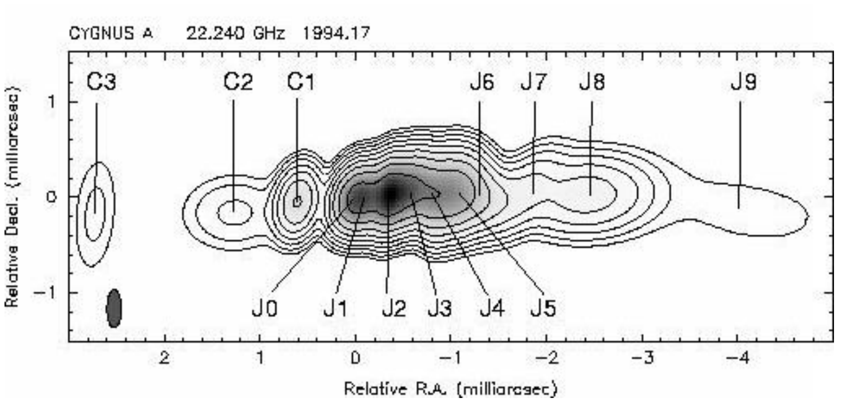




Doppler boosting and jet “sidedness”

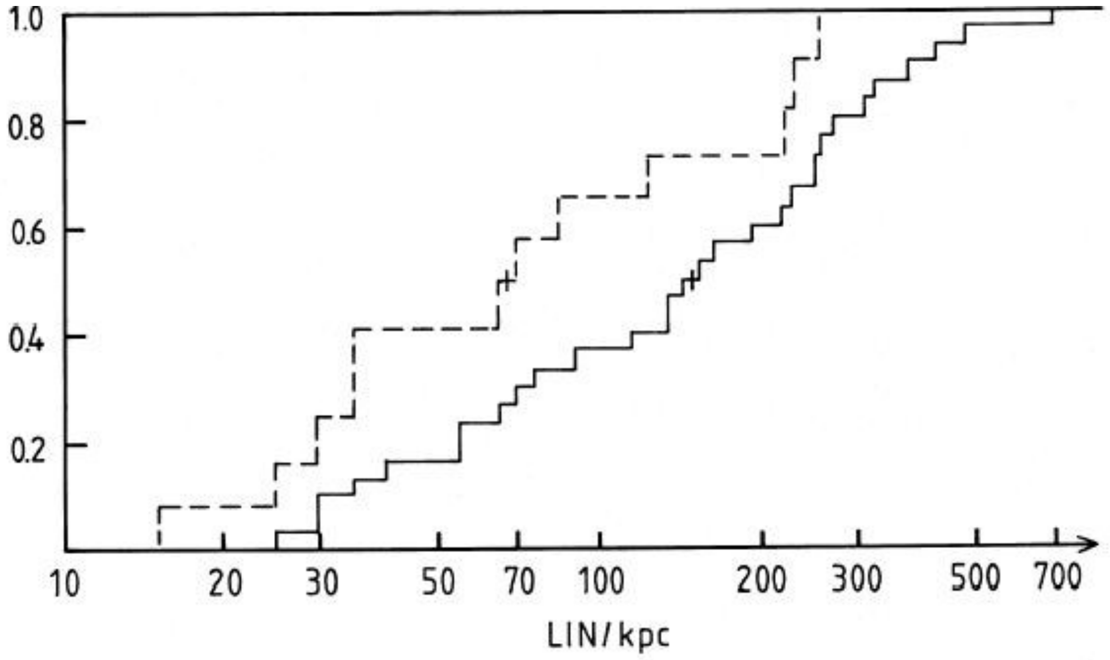
This Doppler boosting gives us one of the main clues that quasars and radiogalaxies are the same type of object, but viewed from different orientations. Looking at large samples of objects we find that that *quasars* tend to have one very bright jet and often no sign of a counterjet; *radiogalaxies* on the other hand often exhibit a jet and a counterjet.





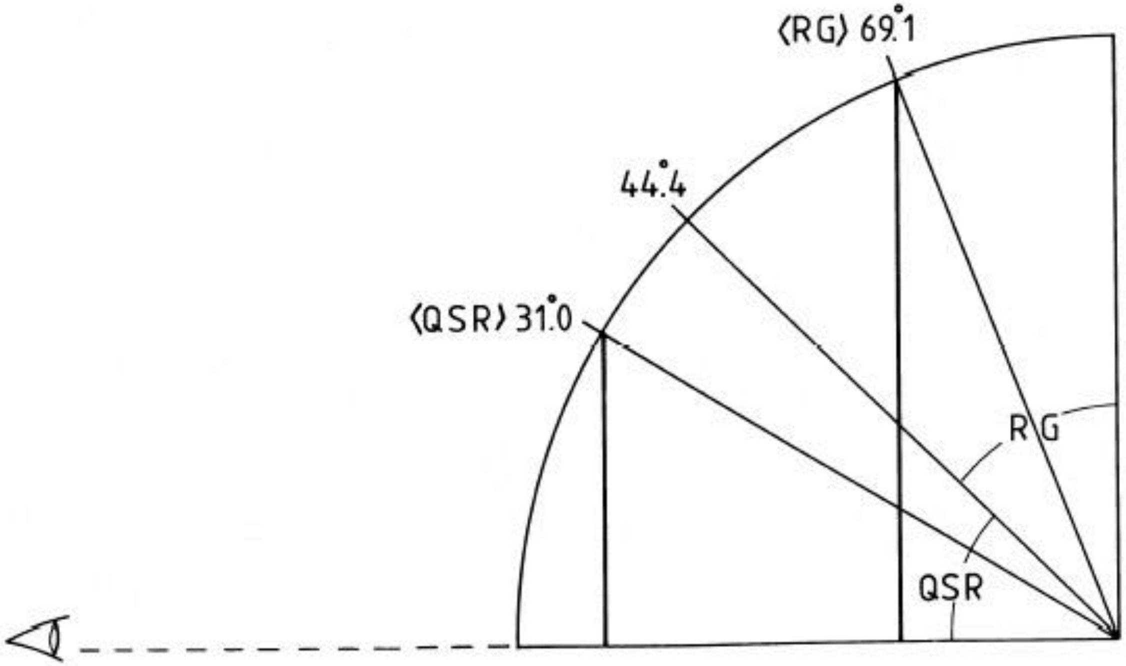
Quasar/radiogalaxy unification

This picture of the quasars “pointing towards us” is neatly supported by the fact that their average projected size is smaller than that of the radiogalaxies:



Cumulative histogram of quasar and radiogalaxy projected sizes.

Quasar/radiogalaxy unification



The ratio of quasar to radiogalaxy mean sizes implies that quasars are seen at an angle of less than ~45° to the line of sight. (Barthel 1989)

Previous

Blog home

Your moons are rubbish, astronomer tells Christmas card artists

Waning crescent moons make a nonsense of Christmas cards depicting snow, carol singers and children decorating trees

An online advent calendar from 2010 shows the moon in the wrong phase for this jolly evening scene in the northern hemisphere. Photograph: www.jacquielawson.com

Posted by
Ian Sample Friday 25 November 2011 15.49 GMT guardian.co.uk
Article history

Science
The moon · Astronomy · Space

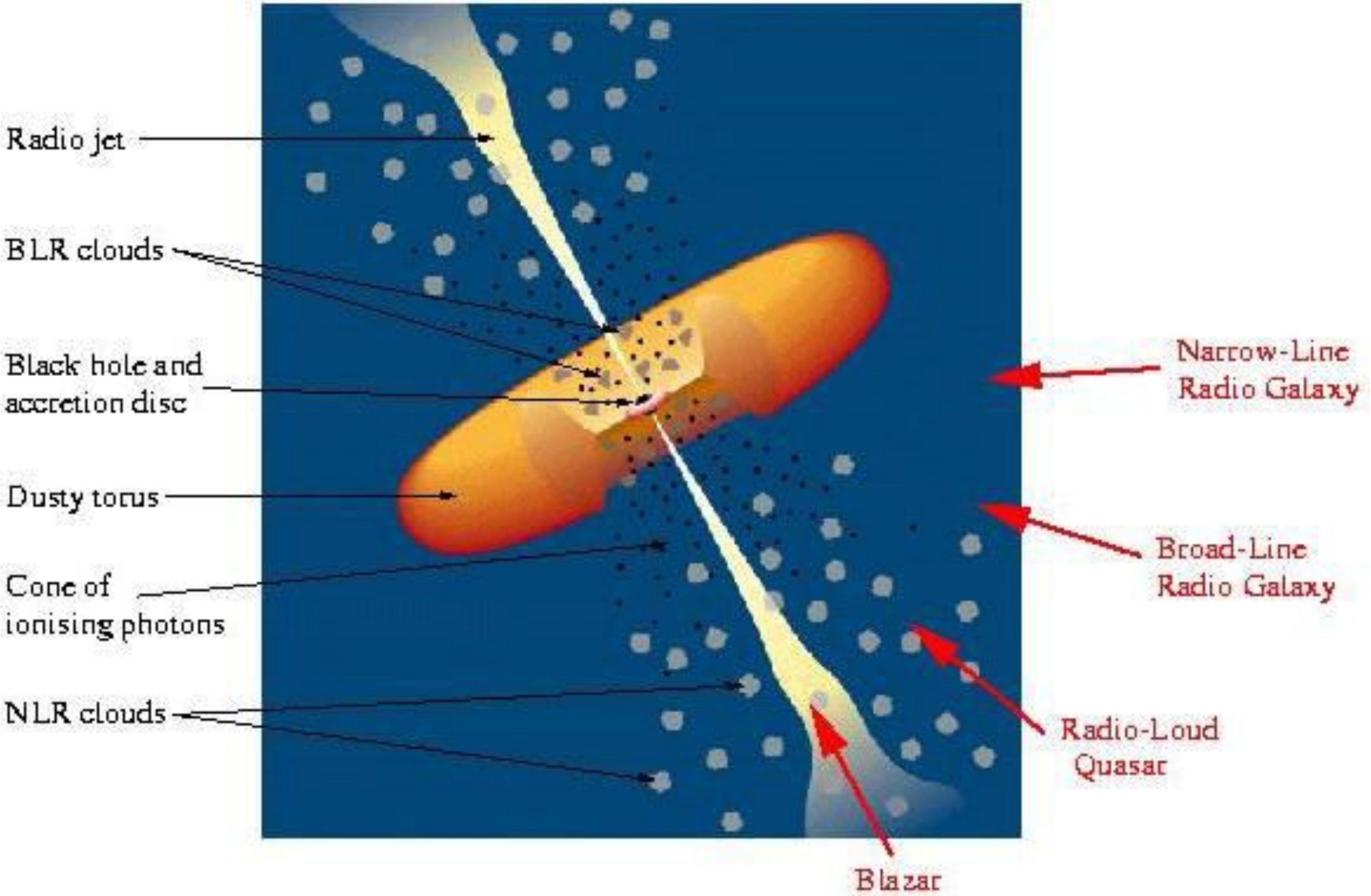
Life and style

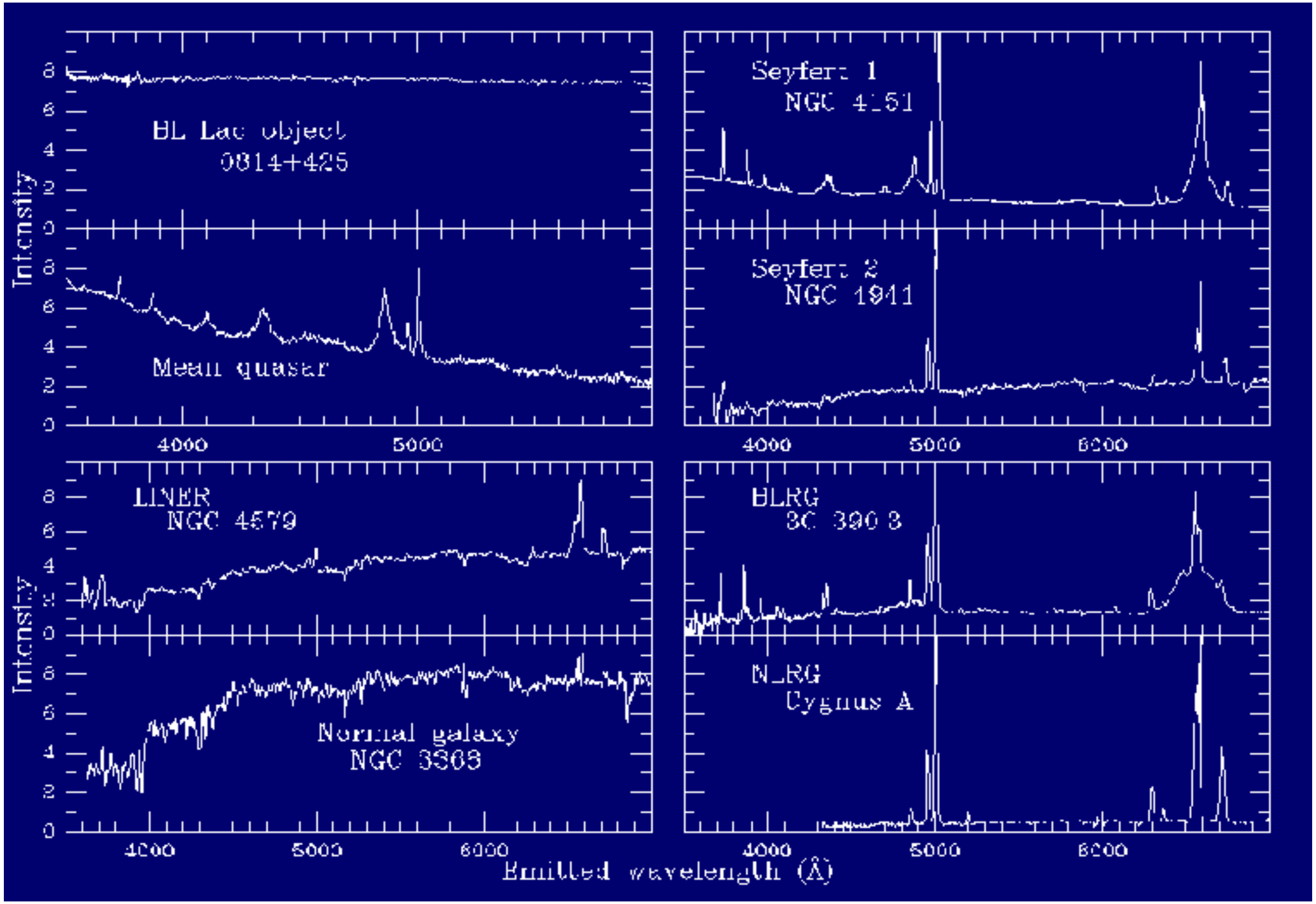
Quasar/radiogalaxy unification

A large body of evidence now exists to support models of orientation-based unification of different classes of AGN. To first order, we can split AGN at any given luminosity into two classes.

- In Type I AGN, we can see the nuclear region directly. The jet axis points towards us and we observe strong Doppler boosting of the jets. Usually the optical/UV continuum emission from the accretion disc, broad emission lines from high-velocity clouds near the nucleus, are visible.

- In Type II AGN, our point of view is more “sideways on”. Our view of the nucleus is obscured by a dusty torus of material beyond the accretion disc. In objects with powerful jets, these tend to be nearly symmetric. Optical emission lines are narrow, originating the in the interstellar medium well away from the nucleus.


Radio jet
BLR clouds
Black hole and accretion disc
Dusty torus
Cone of ionising photons
NLR clouds
Narrow-Line Radio Galaxy
Broad-Line Radio Galaxy
Radio-Loud Quasar
Blazar

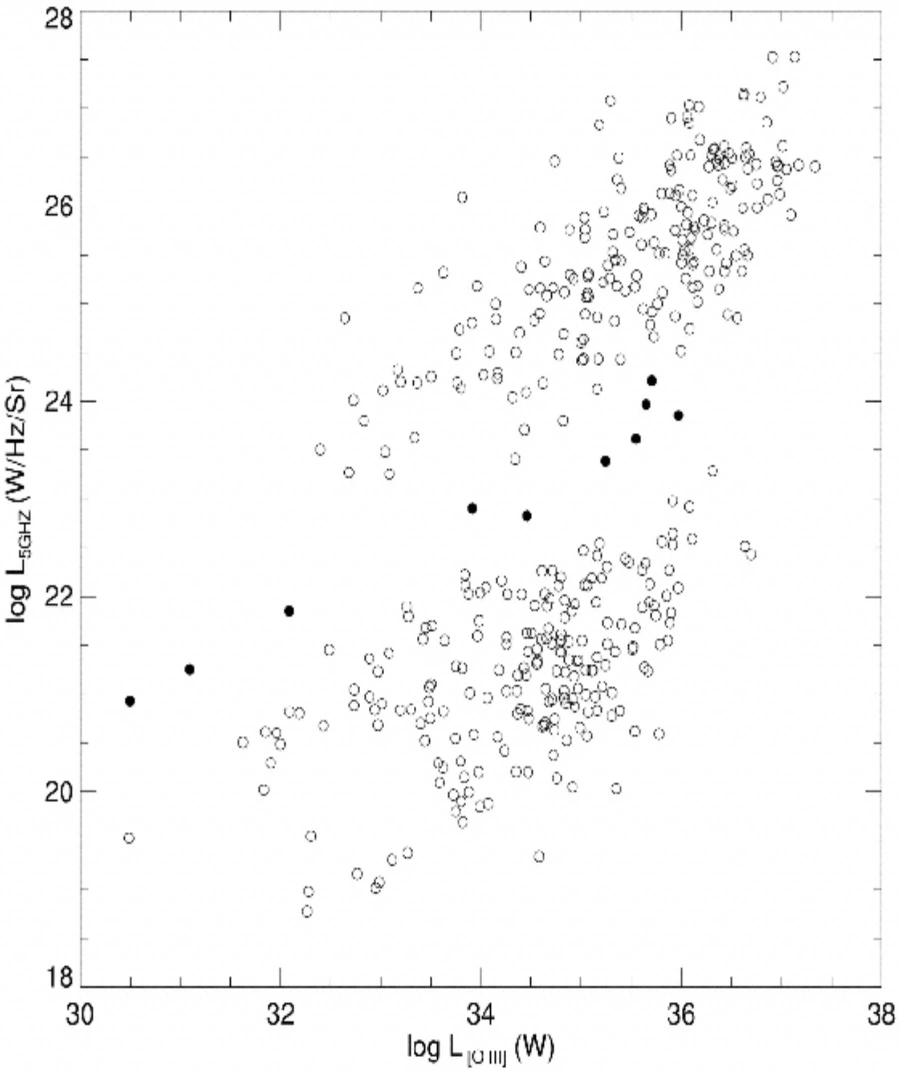

BL Lac object
0814+425
Mean quasar
Seyfert 1
NGC 4151
Seyfert 2
NGC 1941
LINER
NGC 4579
Normal galaxy
NGC 3368
BLRG
3C 390.3
NLRG
Cygnus A
Intensity
0
2
4
6
8
4000
5000
6000
Emitted wavelength (Å)

The radio-loud/radio-quiet dichotomy

Although we now know that even low-luminosity AGN such as Seyferts have jets, the extraordinarily powerful jets of the most luminous sources gives rise to a traditional breakdown of AGN into “radio loud” and “radio quiet” categories.

The classical radiogalaxies and quasars are generally taken to fall into the radio-loud category, and lower luminosity objects such as the Seyferts fall into the radio-quiet class.

However the a complication arises in that there seem to be many objects with the same optical/UV/X-ray properties as the (radio-loud) quasars, but which lack strong radio jets. To avoid confusion we shall refer to these as radio-quiet quasars.

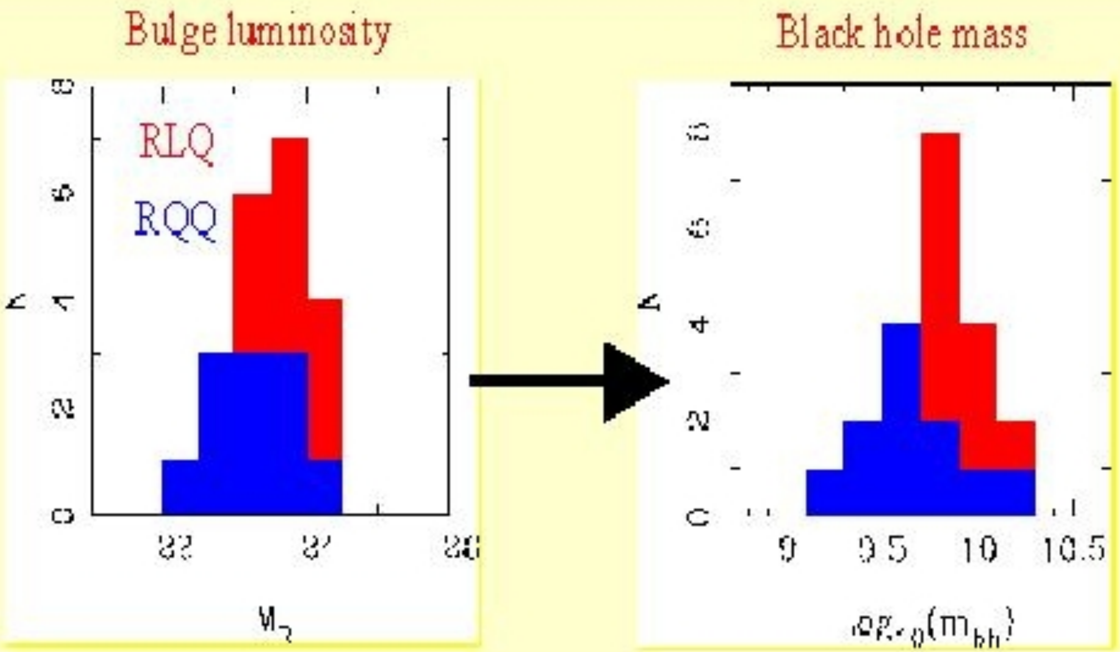

28
26
24
22
20
18
30
32
34
36
38
log L5GHZ (W/Hz/Sr)
log L[O III] (W)

The radio-loud/radio-quiet dichotomy

- Dichotomy: Two separate populations with small number of intermediate cases.
- Correlations: Quasi-thermal emission from the accretion region and non-thermal emission correlated within each sub-class.
- Radio-quiet but not radio-silent: Radio-quiet objects do have jets. Superluminal motions have been detected in some Seyfert galaxies.

But is there really a dichotomy?

- Definitions of radio-loudness: total radio luminosity, extended radio luminosity; radio/optical flux ratio. All have problems.
- Radio-quiet quasars do have radio emission, but this is difficult to detect/image at high redshift, and has been missed in surveys.
- Large, unbiased samples of spectroscopically-selected quasars now available (e.g. SDSS, 2DF).
- Perhaps a steep *luminosity* function for *jet power*.



Bulge luminosity

Black hole mass

$M\,(bh) \sim 10^9 - 10^{10}\ M_0$

Physics of radio-loudness

- BH mass? Radio-loud AGN seem to be associated with the most massive galaxies and therefore (via the bulge luminosity - BH mass correlation) the most massive black holes, but this cannot be the whole story. Why jets?

- Duty cycle? But never see very powerful jets in spiral hosts (do see radio-quiet quasars in spirals)

- Jet disruption in radio-quiets—but low-power jets are seen.

- BH spin may be required for efficient jet production and collimation (e.g via Blandford-Znajek). But no solid evidence yet on BH spin (e.g. from X-ray line profiles).

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BLACK HOLE SPIN AND THE RADIO LOUD/QUIET DICHOTOMY OF ACTIVE GALACTIC NUCLEI

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ABSTRACT

Radio loud active galactic nuclei (AGNs) are on average 1000 times brighter in the radio band compared to radio quiet AGNs. We investigate whether this radio loud/quiet dichotomy can be due to differences in the spin of the central black holes (BHs) that power the radio-emitting jets. Using general relativistic magnetohydrodynamic simulations, we construct steady state axisymmetric numerical models for a wide range of BH spins (dimensionless spin parameter $0.1 \leqslant a \leqslant 0.9999$) and a variety of jet geometries. We assume that the total magnetic flux through the BH horizon at radius $r_{\rm H}(a)$ is held constant. If the BH is surrounded by a thin accretion disk, we find that the total BH power output depends approximately quadratically on the angular frequency of the hole, $P \propto \Omega_{\rm H}^2 \propto (a/r_{\rm H})^2$. We conclude that, in this scenario, differences in the BH spin can produce power variations of only a few tens at most. However, if the disk is thick such that the jet subtends a narrow solid angle around the polar axis, then the power dependence becomes much steeper, $P \propto \Omega_{\rm H}^4$ or even $\propto \Omega_{\rm H}^6$. Power variations of 1000 are then possible for realistic BH spin distributions. We derive an analytic solution that accurately reproduces the steeper scaling of jet power with $\Omega_{\rm H}$ and we provide a numerical fitting formula that reproduces all our simulation results. We discuss other physical effects that might contribute to the observed radio loud/quiet dichotomy of AGNs.

Key words: accretion, accretion disks – black hole physics – galaxies: jets – galaxies: nuclei – magnetohydrodynamics (MHD) – quasars: general – relativistic processes

Online-only material: color figures