There and Back Again: Duty Cycles of Radio Activity

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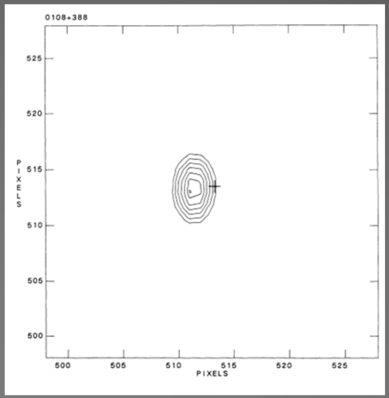
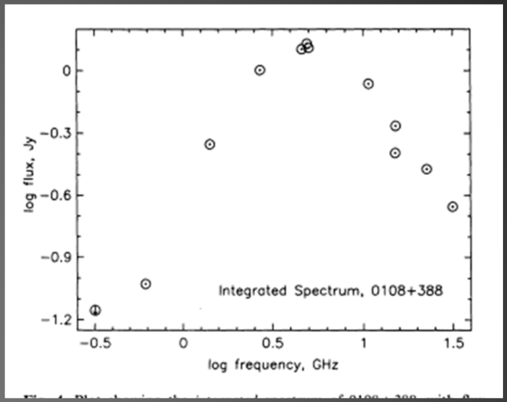
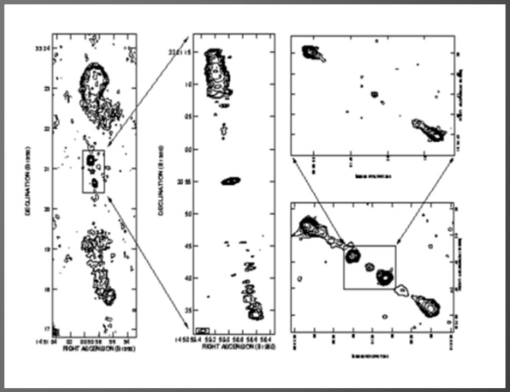
Hercules A. HST & JVLA (O’Dea, Baum, Tremblay, Kharb, Cotton, Perley 2013).

Highlights of Contributions by Ger

- GHz Peaked Spectrum (GPS) radio galaxies are thought to be young compact radio galaxies which will evolve to become large radio galaxies. 0108+388 shows extended emission possibly from a previous epoch of activity.
- Double-Double Radio Galaxies are large classical double radio sources with a much smaller double radio source nested within. These are thought to represent repetitive activity.







(Top Left) GPS source 0108+388 WSRT 49 cm image with pt source subtracted showing extended low frequency component. (Top Right) Radio spectrum of 0108+388 (Baum+1990). (Bottom) Double-Double radio galaxies (Schoenmakers+ 2002)

Outline

- The Duty Cycle (Schmidt 1966)
- Why Do we Care about the Duty Cycle?
  - M-σ
  - Galaxy luminosity function
  - Cooling core clusters
- Observational Constraints
  - Radio Power vs Galaxy Mass
  - Two Accretion Modes
  - Repetition (example Hercules A)
- What did we Learn?

The Duty Cycle of Radio Galaxies

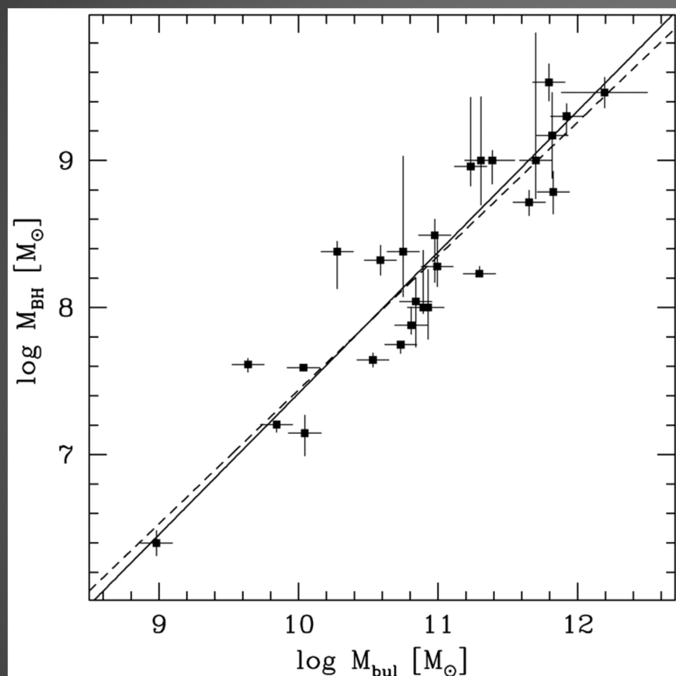
- Duty Cycle is fraction of the time that a radio galaxy is active.

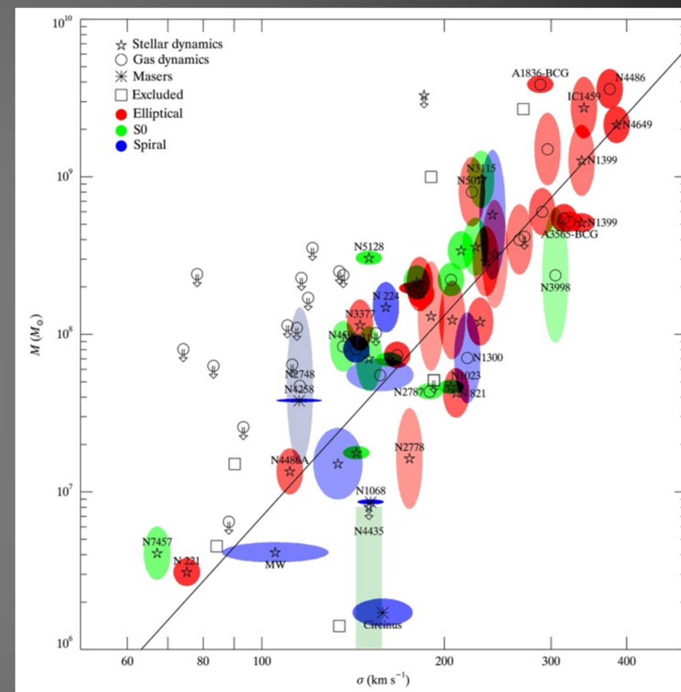
  Duty Cycle = $\frac{T_R}{T_E} = \frac{N_R}{N_E}$

- Statistical approach (Schmidt 1966) where T is the lifetime, N is the number density, R refers to radio galaxy and E refers to Elliptical galaxy. T_R may include multiple episodes of activity.

- The Duty Cycle constrains the physics of
  - Radio (Mechanical) Mode Feedback
  - BH fuelling and jet launching

Black Hole Mass Scales with Galaxy Bulge Mass





(Left) BH mass vs. Bulge Mass (Marconi & Hunt 2003). (Right) M-σ relation for galaxies with dynamical measurements. The symbol indicates the method of BH mass measurement: stellar dynamical (pentagrams), gas dynamical (circles), masers (asterisks). Arrows indicate 3σ6 8upper limits to BH mass. For clarity, we only plot error boxes for upper limits that are close to or below the best-fit relation. The color of the error ellipse indicates the Hubble type of the host galaxy: elliptical (red), S0 (green), and spiral (blue).. The line is the best fit relation to the full sample: $M_{BH} = 10^{8.12}\ M_{\odot}(\sigma/200\ km/s)^{4.24}$. For clarity, we omit labels of some galaxies in crowded regions (Gultekin+2009).

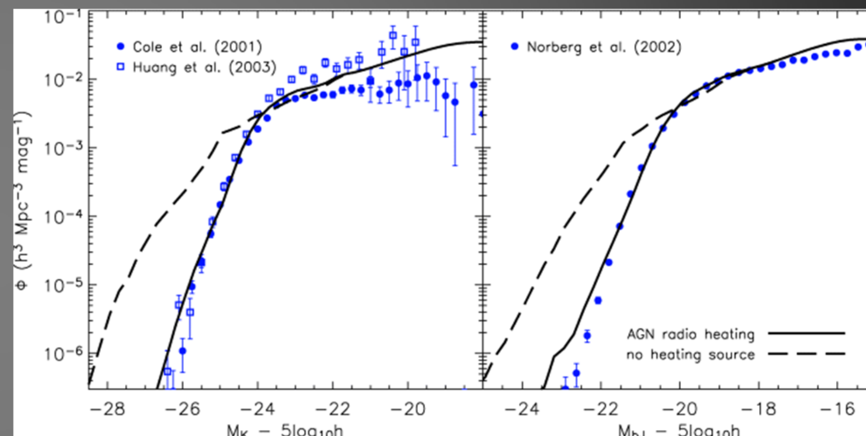
Radio Galaxy Feedback Invoked to Explain Galaxy Formation

- We seem to need radio feedback to prevent over cooling and to reproduce the bright end of the galaxy luminosity function.

- Star formation in the most massive galaxies must be suppressed.

- On what time scales is radio feedback generated?

- What Physics determines those time scales?

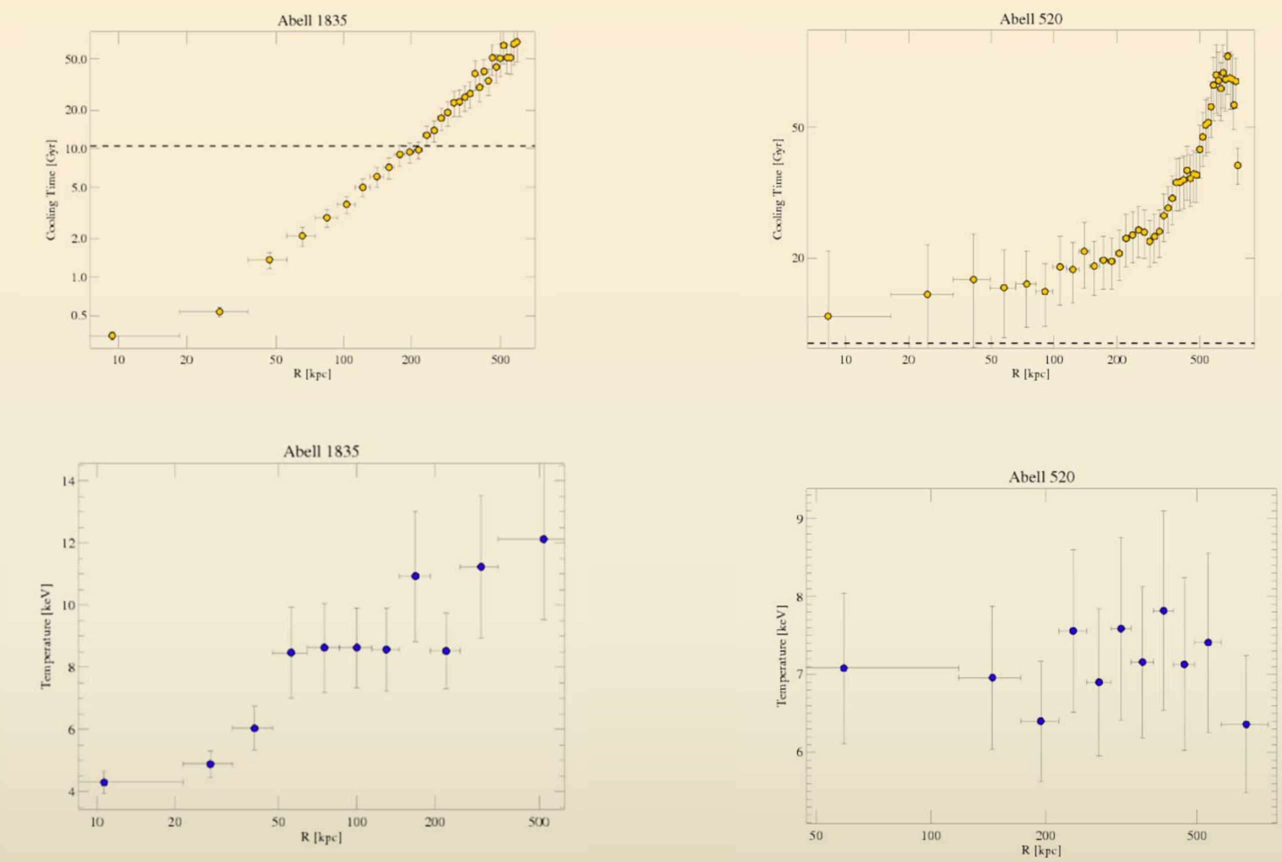


Galaxy luminosity functions in the K (left) and bJ (right) photometric bands, plotted with and without 'radio mode' feedback (solid and long-dashed lines respectively). Symbols indicate observational results as listed in each panel. (Croton+2005).

Cooling Core and Isothermal Clusters

Cooling Time (Gyr)

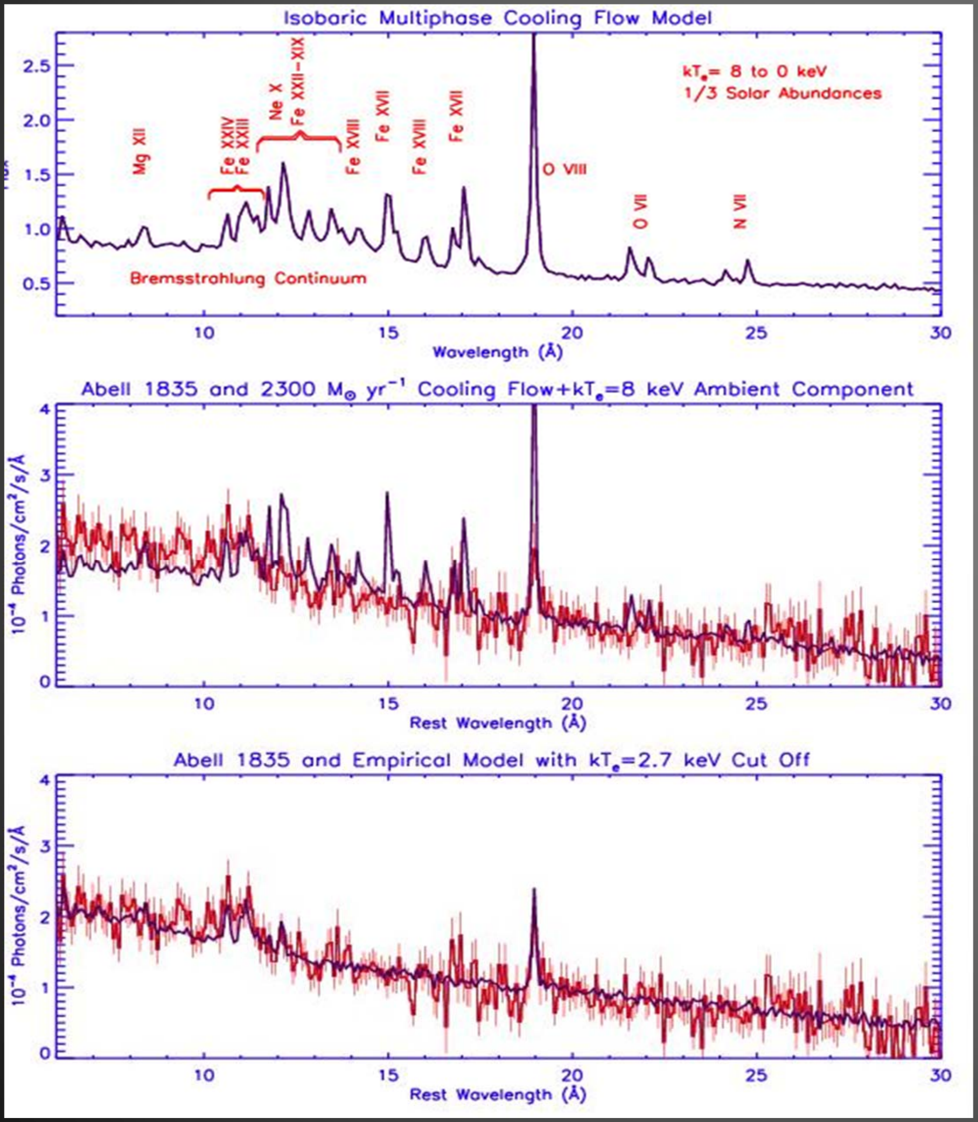
Temperature (keV)



Distance from center (kpc)

(Left) Cooling Core cluster A1835. (Right) Isothermal cluster A520.
(Cavagnolo+ 2009)

Failure of the Cooling Flow Model

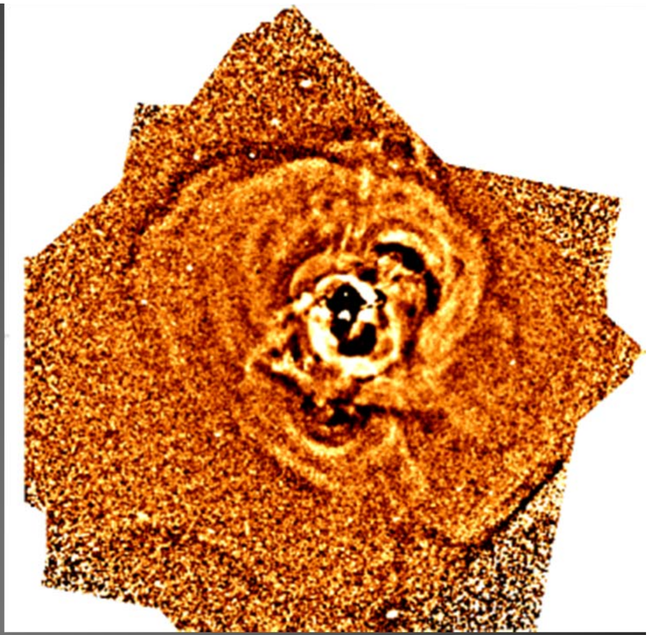


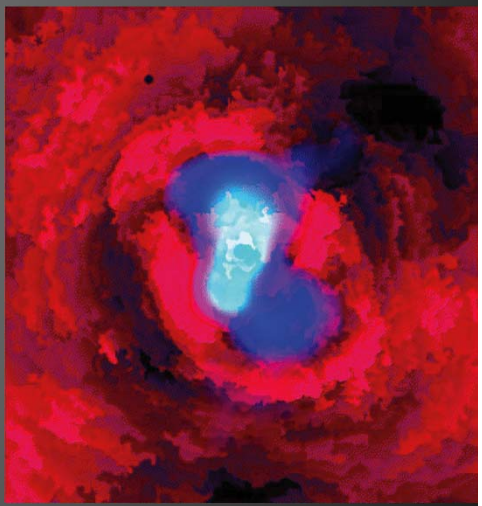
8 keV → 3 keV → ?

Peterson et al. 2003, ApJ, 590, 207

System of Nested Ripples/Bubbles in Cooling Flow ICM

- multiple episodes (or semi-continuous?) radio activity – driven by the availability of fuel?
  - are required to account for the heating of the ICM



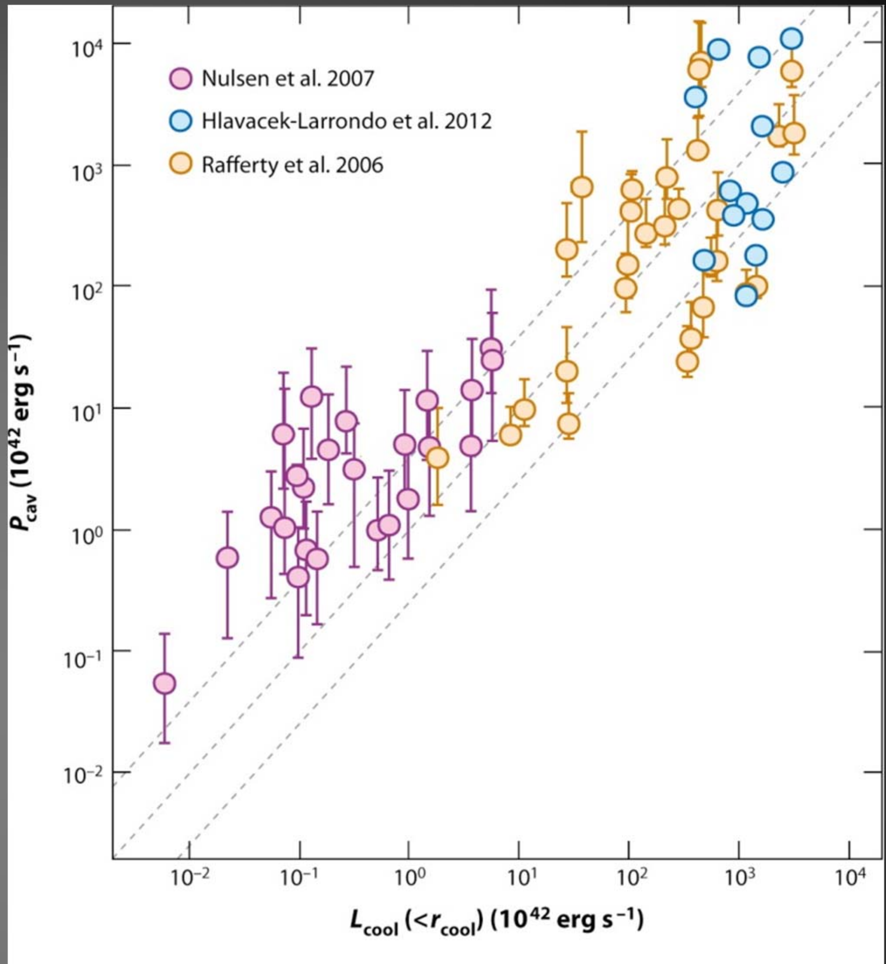


(Top) Unsharp masked image from Chandra Image. (Bottom) Radio image in blue superimposed on pressure difference map in red (Fabian et al 2006).

Cavity power is comparable to cooling luminosity

This indicates the cavities have sufficient power to resupply the cooling gas. But how does it do it?

This correlation suggests that the powers are linked by a feedback mechanism.



Fabian AC. 2012.
Annu. Rev. Astron. Astrophys. 50:455–89

Power inferred from cavities/bubbles plotted against luminosity within the cooling region (where the radiative cooling time is less than 7 Gyr). The objects range from luminous clusters, through groups, to elliptical galaxies.

- Early discussions of the role of radio sources in cooling flows suggested the energy was available (Tucker & Rosner 1983; Pedlar et al. 1990; Baum & O'Dea 1991; Binney & Tabor 1995; Sarazin, Baum, O'Dea 1995; Tucker & David 1997)

Mon. Not. R. astr. Soc. (1991) **250,** 737–749

Multifrequency VLA observations of PKS 0745 − 191: the archetypal 'cooling flow' radio source?

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SUMMARY

We present 90-, 20-, 6-, and 2-cm VLA§ observations of the high radio luminosity, cooling flow radio source PKS 0745 − 191. We find that the radio source has a core with a very steep spectrum ($\alpha \simeq -1$) and diffuse emission with an even steeper spectrum ($\alpha \simeq -1.5$ to -2.3) without clear indications of the jets, hotspots or double lobes found in other radio sources of comparable luminosity. The appearance of the source is highly dependent on frequency and resolution. This dependence reflects both the diffuse nature of the extended emission and the steep, but position-dependent, spectrum of the radio emission.

The cooling flow itself and processes associated with it are unable to provide sufficient energy to power the radio source. This includes energy input from shocks, supernovae, and magnetic reconnection in the inflowing, cooling gas. Thus, we favour an interpretation in which the energy input comes from the central engine, but in which the structure of the source may be heavily influenced by the past history of the galaxy and the inflowing intracluster medium.

We show that, while the radio source is energetically unimportant for the cluster as a whole, it is certainly important on the scale of the cooling flow. The radio source should be an important source of local heating, in the form of kinetic energy, cosmic rays, and enhancement of thermal conductivity. The mere existence of cosmic rays and magnetic fields within a substantial fraction of the volume inside the cooling radius has important consequences for cooling-flow models. Since the radio data imply that large amounts of energy are being deposited in the cluster core, we suggest that non-steady state models for the cooling flow in PKS 0745 − 191 should be considered.

1 INTRODUCTION

In the standard 'cooling flow' models of the intracluster medium, hot (10^7–10^8 K) gas with a cooling time less than the Hubble time cools and falls quasi-hydrostatically into the centre of the cluster potential well. There, it is expected to be accreted by the central dominant galaxy of the cluster. Indeed, such 'cooling flow' models have successfully reproduced the radial profiles of temperature and density in the intracluster gas inferred from X-ray imaging and X-ray spectroscopic observations, providing strong, albeit circumstantial, evidence that cooling flows do exist (see Fabian, Nulsen & Canizares 1984; Sarazin 1986 and references therein). These cooling flow clusters have also been shown to have large Hα luminosities indicating the presence of gas at 10^4 K (Heckman 1981; Cowie *et al.* 1983; Hu, Cowie & Wang 1985; Johnstone, Fabian & Nulsen 1987), although the mechanism by which this gas is maintained at these temperatures is a point of much debate. Typical mass accretion rates inferred in these cooling flow clusters are 100 $M_\odot$ yr^{-1} within a region 100 kpc in radius. If cooling flows of the magnitude presently proposed do in fact exist, then they must have a profound effect on shaping the distribution of matter in clusters, in groups of galaxies, and perhaps in individual galaxies, and may also provide fuel for the central engine in AGNs.

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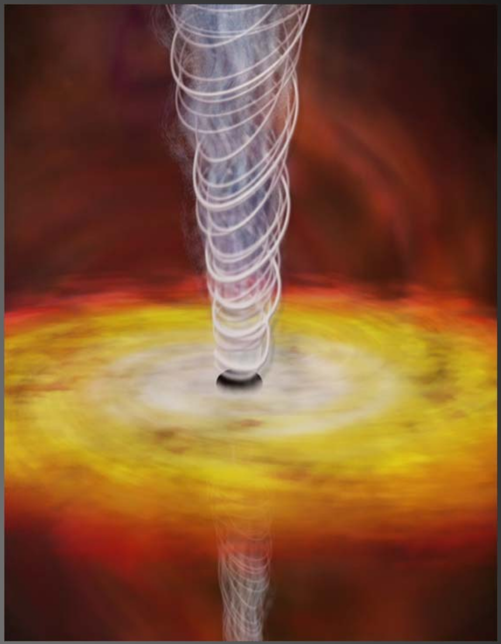
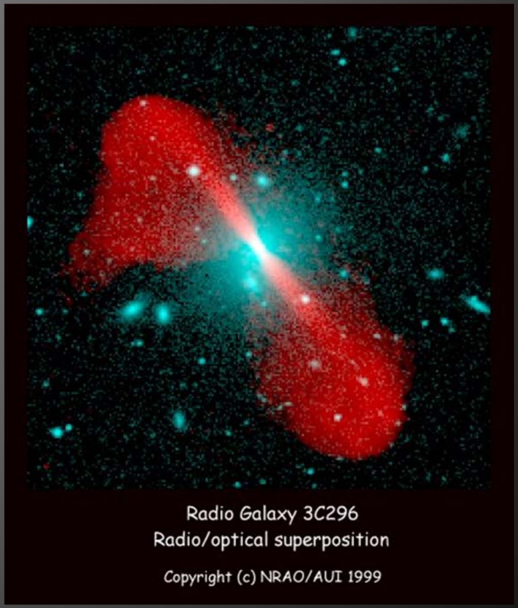
Radio Loud AGN

- Supermassive Black Hole
- Fuel Supply (merger/interaction or cooling flow)
- Accretion Structure (disk, RIAF)
- Relativistic Jet (relativistic particles, magnetic fields)
- BH Spin (may be required to launch jet)

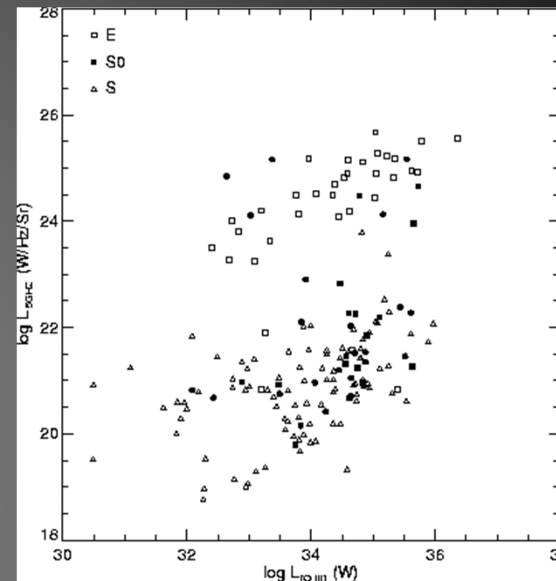


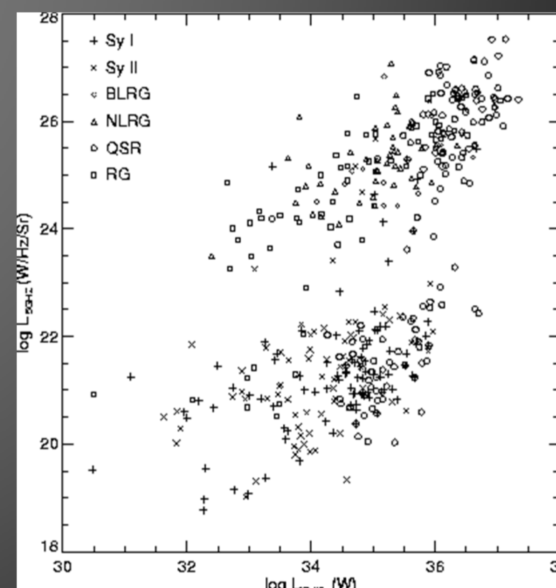


What Does Radio Output Depend on?

Some AGN with luminous accretion disks are not powerful radio sources. So high accretion rate is not sufficient to produce powerful radio jet. There must be another parameter (BH spin?)

Powerful radio jets seen preferentially in Elliptical galaxies (bigger bulges?)





[OIII] luminosity used as a proxy for accretion disk luminosity.
(Chun, Livio, Baum, 1999)

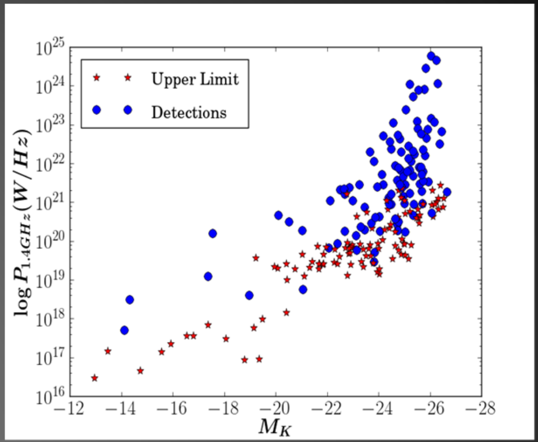
Maximum Radio Power Scales with Galaxy/BH Mass

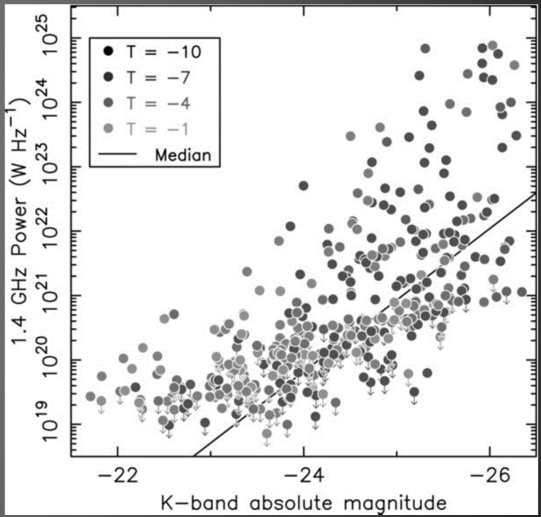
The maximum possible radio power is a function of galaxy luminosity (Galaxy and/or BH Mass). Benefit: Radio feedback occurs preferentially in the most massive galaxies where it is "needed."

There is a dispersion in radio power at a given galaxy stellar luminosity. Galaxy stellar mass (BH Mass) is clearly one critical parameter, but not the only one.

What regulates the radio power?

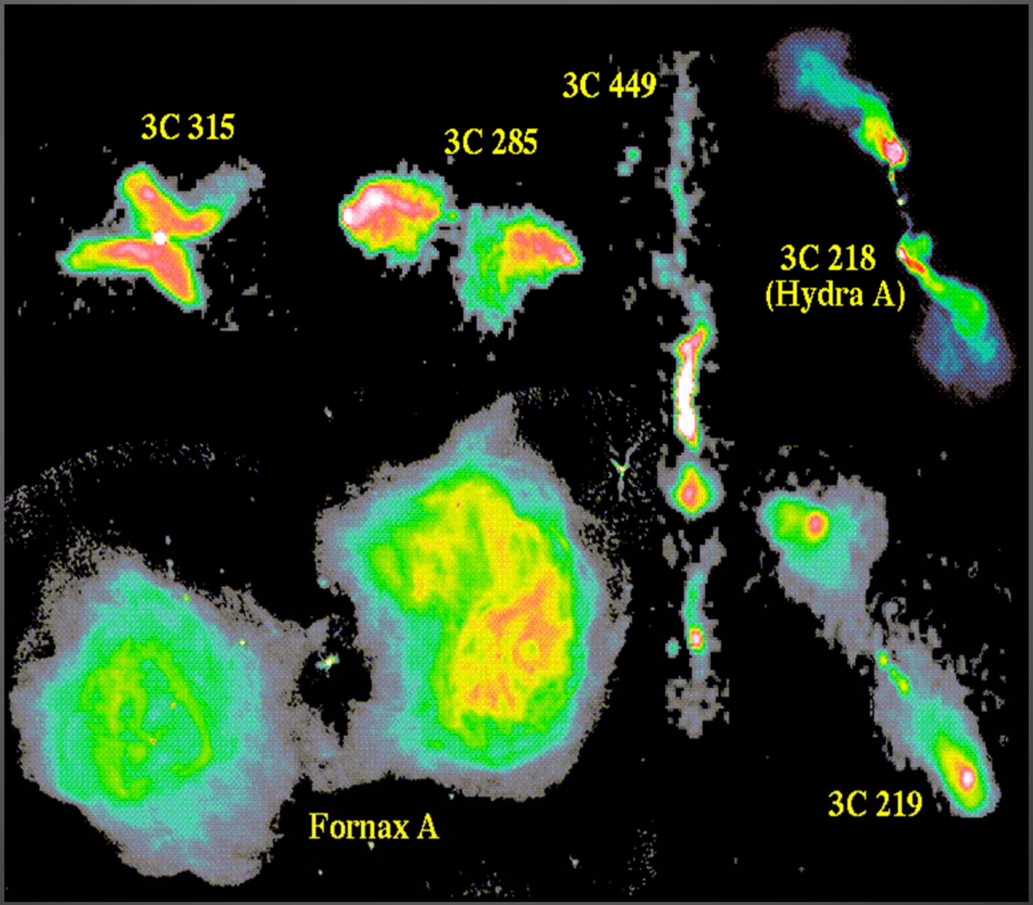
Why does BH (or Bulge) Mass matter so much?





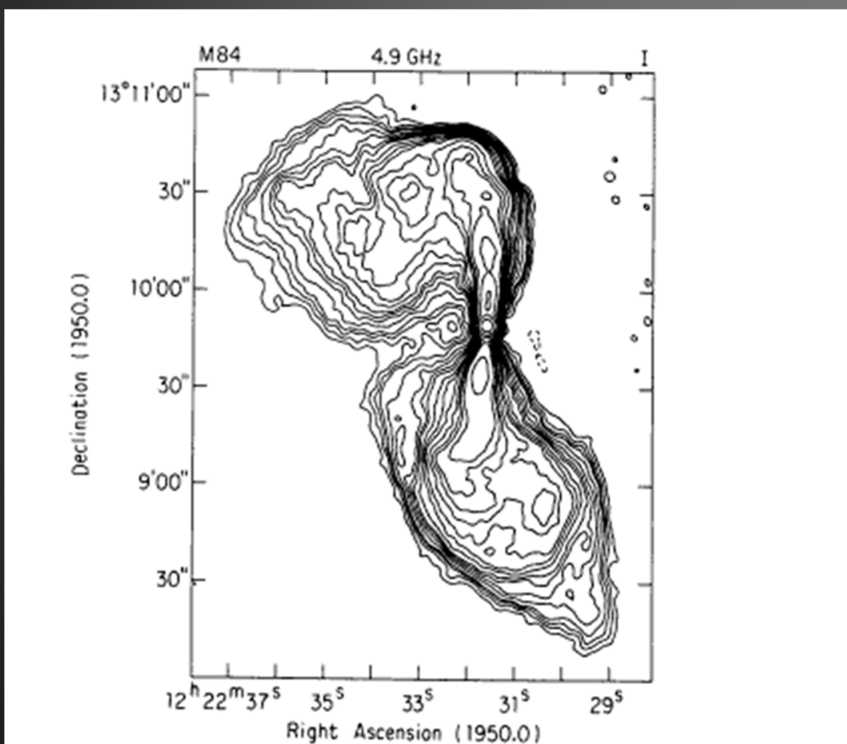
(Top) Radio Power vs. Absolute K magnitude in an optically selected sample of nearby elliptical galaxies (Vaddi, O'Dea, Baum+ 2012). (Bottom) 1.4 GHz radio power of early-type galaxies as a function of K-band absolute magnitude. The data are color coded by RC3 T type and for sources with measured flux densities less than 2σ above zero, we plot 2σ upper limits. At a fixed absolute magnitude, the distribution of radio powers spans four orders of magnitude for early-type galaxies brighter than MK = –24 (Brown+2011).

Diversity of radio properties reflect both launch of jet and subsequent propagation.

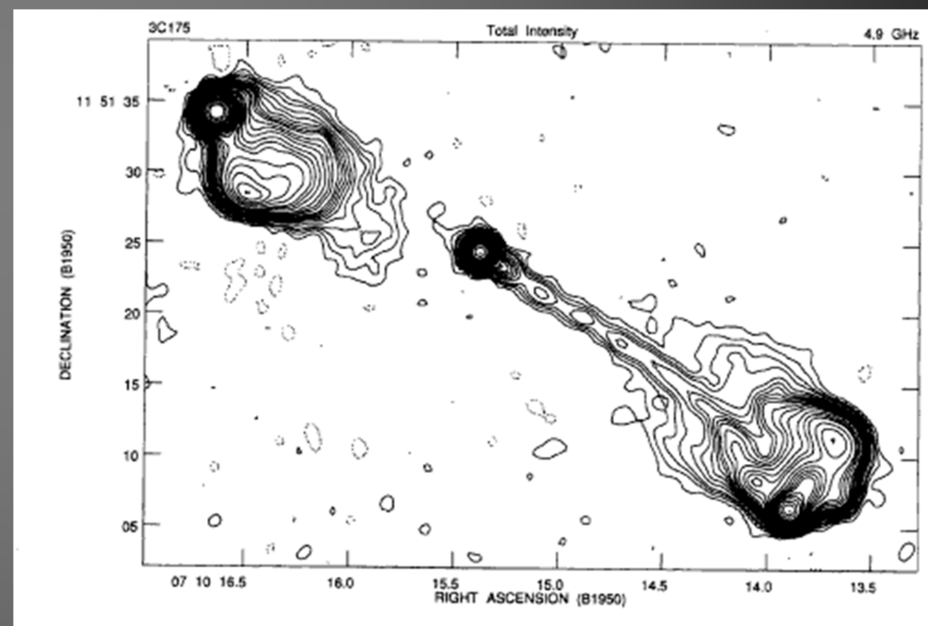


Two main flavors of Radio Structure

Fanaroff and Riley Class I



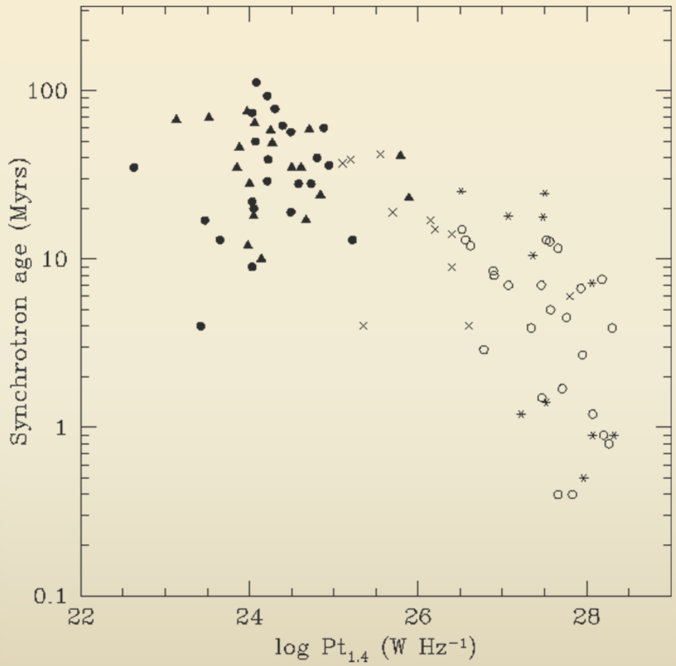
Fanaroff and Riley Class II



Laing and Bridle 1987
Bridle et al 1994

Do Low Power Radio Galaxies Live Longer ?

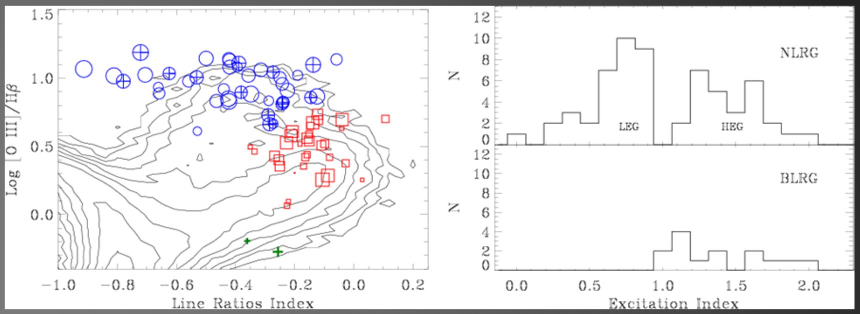
- Low power sources have spectral and dynamical ages t ~ 10^{7-8} yr
- High power sources have ages t ~ 10^{6-7} yr
- Whatever drives RG evolution (Fueling modes?) has two different time scales in the two types of sources.
- But beware uncertainties in age estimates.

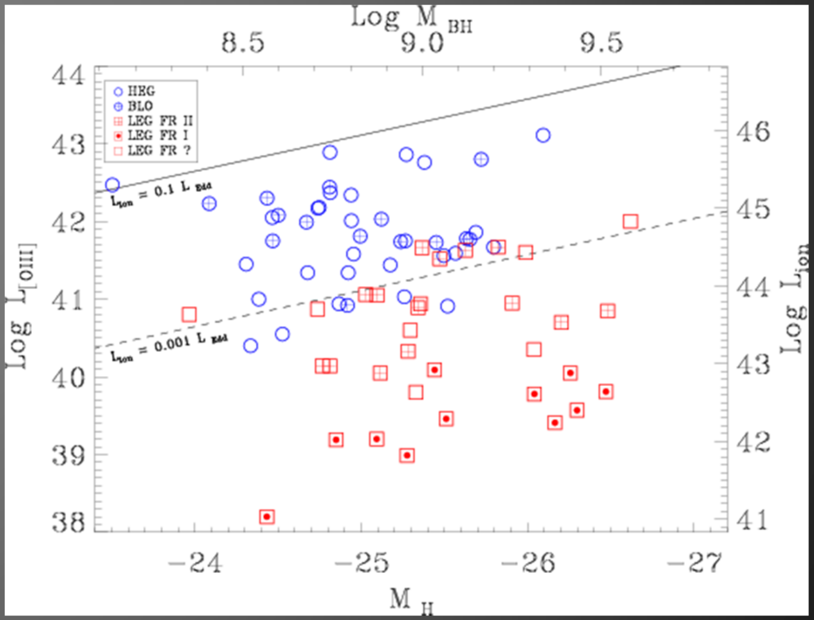


Estimated synchrotron ages vs radio power at 1.4 GHz for a sample of radio galaxies. Filled circles and triangles: B2 sources with type 1 and type 2 spectra, respectively; crosses: 3C galaxies with z < 0.2; open circles: 3C galaxies with z > 0.2; asterisks: 3C quasars. (Parma+ 1999)

High and Low Excitation Emission Lines

- Emission line properties of radio galaxies divide into high and low excitation (e.g., Laing+ 1994). High excitation lines require a bright accretion disk and thus high mass accretion rates.
- The line excitation is independent of galaxy and BH mass.
- HEG are nearly all FRII, but LEG are a mix of FRI and FRII.



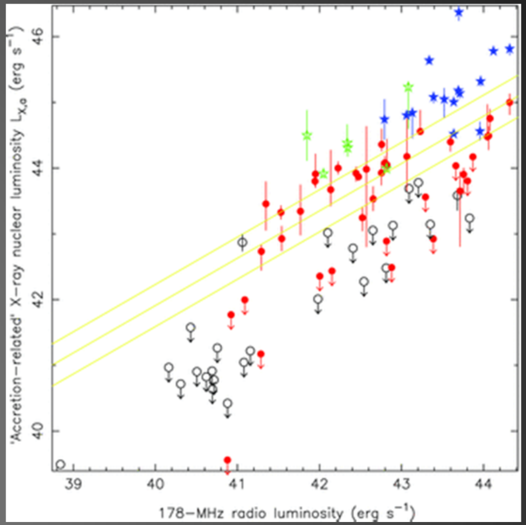


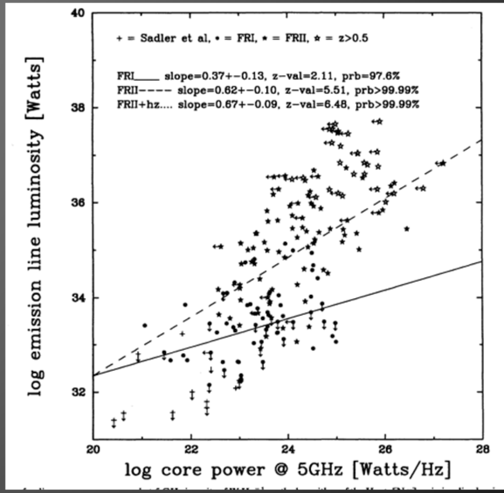
(Top) Left panel: LRI vs. log [O III]/Hβ including the broad line objects (crossed circles) and zooming onto the 3CR populated region. HEG are represented by circles, LEG by squares. Right panel: comparison of the distributions of excitation index for narrow and broad line objects. (Bottom) Comparison of [O III] line luminosity (in erg/s) and H band host magnitude for 3CR sources. Symbols are HEG = blue circles, LEG = red squares (filled for FR II, crossed for FR I, empty for uncertain FR type. The right axis reports the ionizing luminosity (in erg/s) while the upper axis reports the estimated black hole mass in solar units. The solid and dashed lines correspond to \$L $_{ion}$ = 0.1 L $_{Edd}$ and 0.001 L $_{Edd}$, respectively. (Buttiglioni+2010).

Line Ratio Index LRI= 1/3 (log [N II]/Hα + log [S II]/Hα + log [OI]/Hα. Excitation Index EI = log [O III]/Hβ – LRI (Buttiglioni+2010)

Two Accretion Modes

- At a given radio power, FRIs have fainter nuclear X-ray and UV emission, suggesting they have fainter/absent accretion disks.
- Two different accretion modes (e.g., Fabian & Rees 1995; Baum, Zirbel, O'Dea 1995).

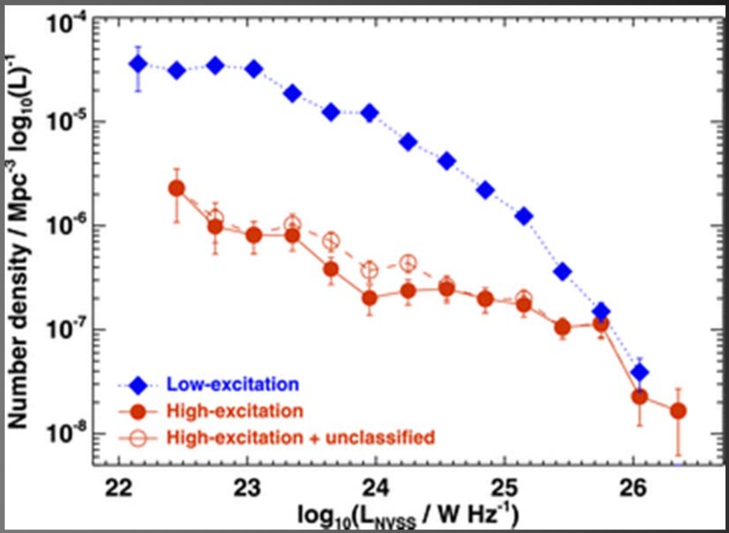


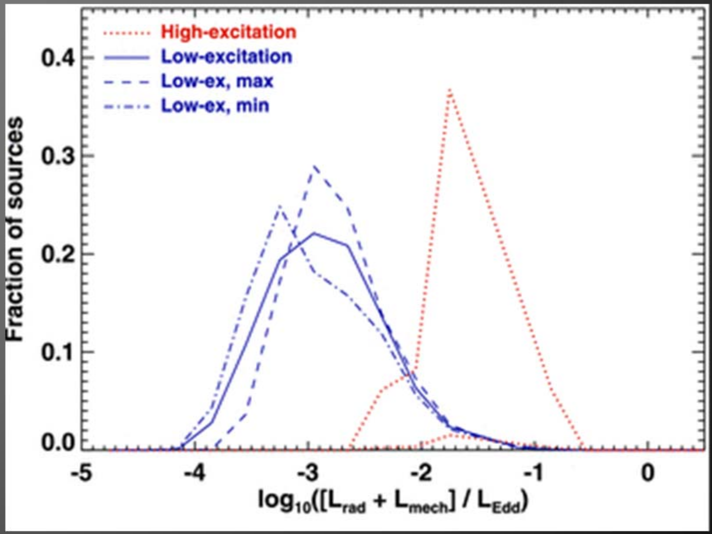


(Top) X-ray luminosity for the 'accretion-related' component, LXa, as a function of 178-MHz total radio luminosity for the z < 1.0 3CRR sample. Black open circles indicate LERGs, red filled circles NLRGs, green open stars BLRGs and blue filled stars quasars. Regression is for detected NLRGs only. Upper limits assume $N_H= 10^{23}$ cm^{-2}. It can be seen that the upper limits for the LERGs lie systematically below the regression line. (Hardcastle+ 2009). (Bottom) Optical line luminosity vs. radio core luminosity. (Baum, Zirbel, & O'Dea 1995)

Two Accretion Modes

- At low radio power the LEGs dominate. These low powers are characteristic of FRIs. Thus, at the lower powers, LEGs have higher duty cycle (i.e., have longer lifetimes or are active more frequently) than HEG.
- At the higher radio powers the numbers of HEG and LEG are more comparable.
- Radio jets produced in both accretion modes.

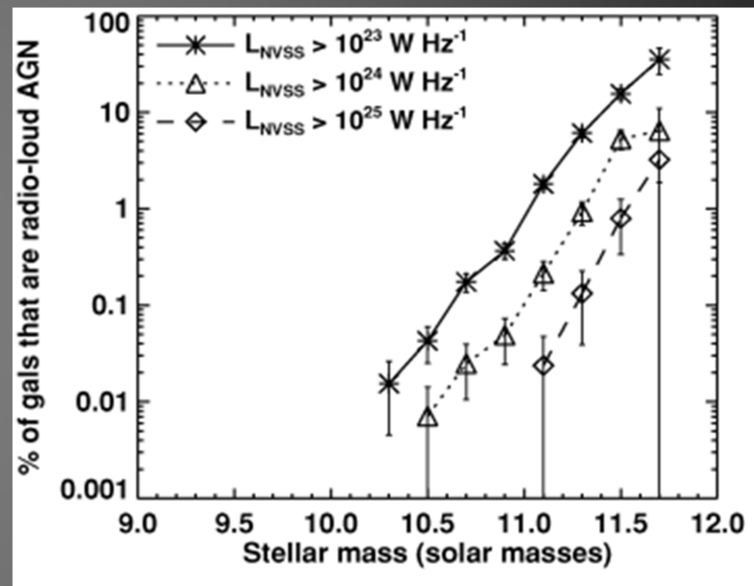




(Top) The local radio luminosity function at 1.4 GHz, derived separately for the HERG and LERG populations. (Bottom) the distribution of Eddington-scaled accretion rates for the LERG and HERG populations separately. For the LERGs, the solid line shows the best estimate distribution, using the calculated values of the radiative luminosity. For the HERGs, the dotted line is plotted with two different normalizations: the upper line shows the fraction of sources relative to the total number of HERGs, while the lower line shows the fraction relative to the total number of LERGs to allow direct comparison of numbers with the LERGs. (Best & Heckman 2012).

Duty Cycle Scales with Radio Power and Galaxy Mass

- Massive galaxies are radio sources more frequently.
- Galaxies are active more often at lower radio power.



The fraction of galaxies which are radio-loud AGN, as a function of stellar mass (Best+2005).

Why does Radio Power Scale with BH Mass?

Argument based on scaling relations (Best+ 2005).

$M_{cool} \sim \frac{M_{gas}}{t_{cool}} \sim \frac{L_x}{T}$ expected Mass cooling rate

$T \sim \sigma^2$ for isothermal gas

$L_x \sim L_{opt}{}^2$ empirical (O'Sullivan+ 2001)

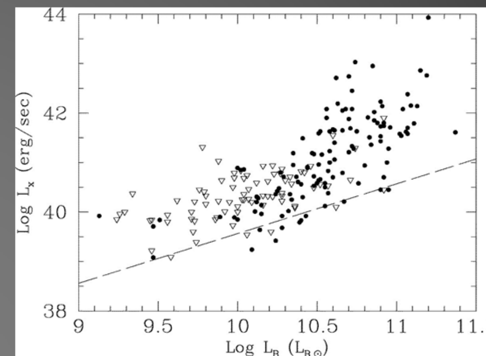
$L_{opt} \sim \sigma^4$ empirical (Faber-Jackson)

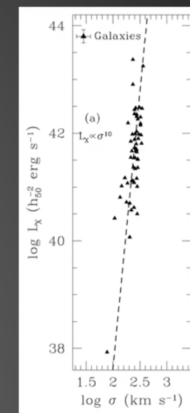
Then $L_x \sim \sigma^8$ (consistent with Mahdavi & Geller 2001).

$M_{bh} \sim \sigma^4$ empirical (M-σ relation, e.g., Gultekin+2009)

$M_{cool} \sim \frac{L_x}{T} \sim \sigma^6 \sim M_{bh}{}^{1.5}$

More cooling in the ISM of massive galaxies.

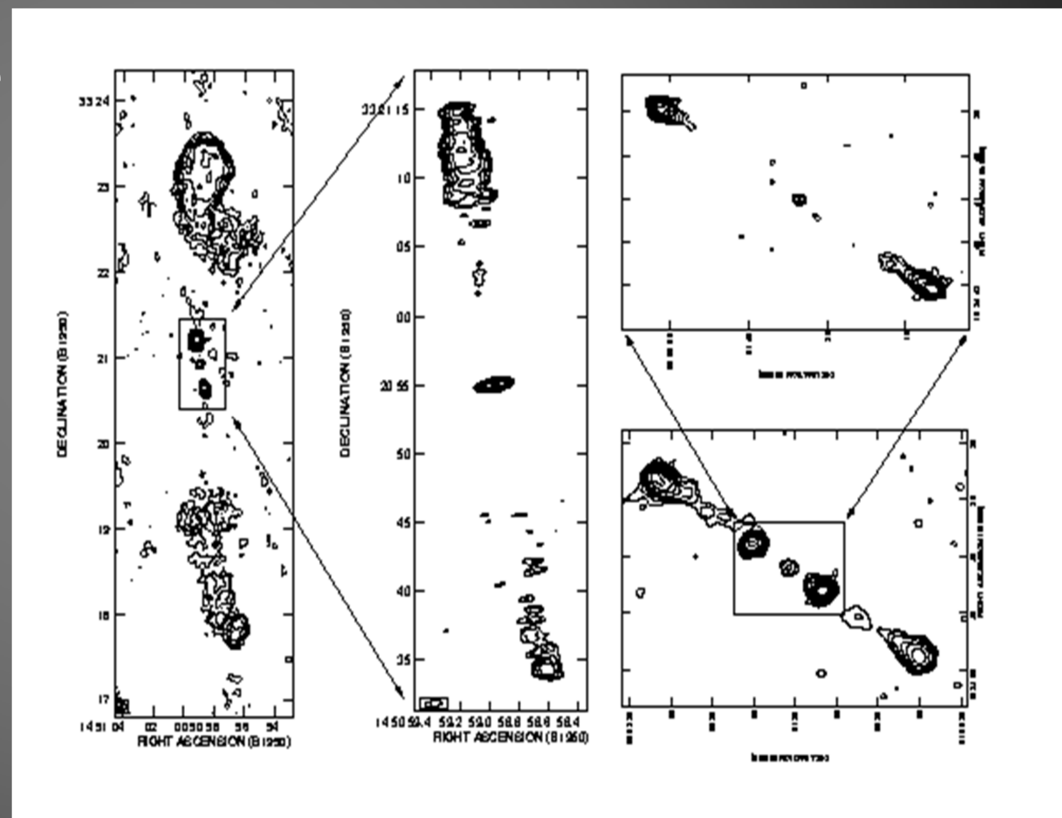




(Left) L_x vs. L_B i.e., bolometric X-ray luminosity and B-band optical luminosity for elliptical galaxies (RC3 type T ≤−4). X-ray detections are shown with filled circles and upper limits with open triangles. The dashed line is an approximate locus of the total luminosity $L_{x,*} \sim L_B$ of stellar and other discrete sources also (O'Sullivan+ 2001; Mathews & Brighenti 2003). (Right) Lx – σ relation for galaxies (Mahdavi & Geller 2001).

Are Double-Doubles Born Again?

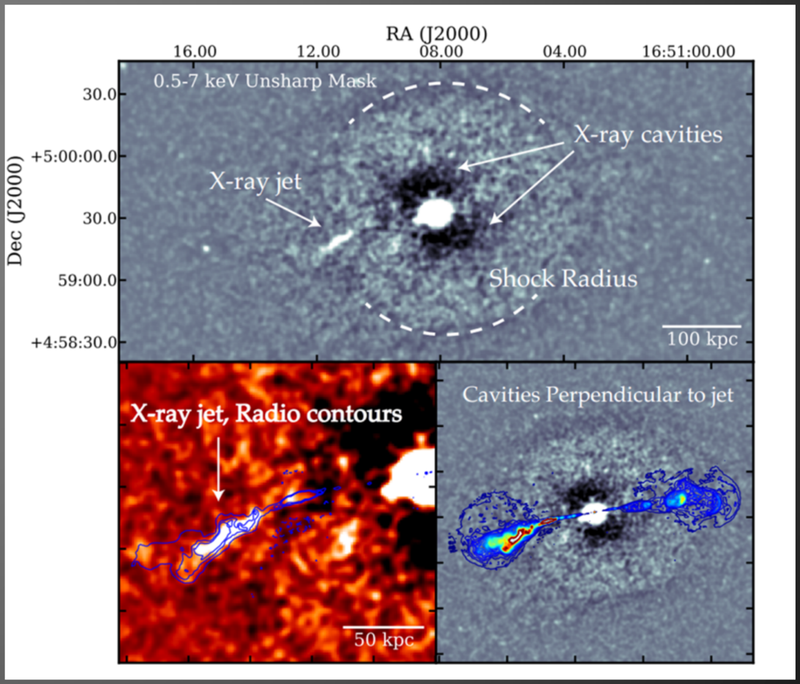
- **5-10% of > 1 Mpc radio sources show double-double structure.**
- **Working hypothesis: the radio galaxy turned off and then turned back on -- creating a new double propagating outwards amidst the relic of previous activity (**Schoenmakers+ 2000**).**



Schoenmakers et al. (2002)

Why are cavities misaligned with radio axis? Black Hole Spin Flip?

- Current radio source might be few -10x10^6 yr old (radiative lifetime, dynamics).
- Shock and cavities possibly 60-70 x10^6 yr old (dynamics).
- Perhaps cavities were created by a previous radio source along the cavity axis, followed by a BH spin flip (e.g., Merritt & Ekers 2002) before the current radio source became active.



Hercules A. VLA and Chandra observations (O'Dea+2013, Tremblay+2014). Cavities and shock reported by Nulsen+2005.

Summary I

- Radio Jets require a supply of gas, but it doesn't matter whether it is a luminous accretion disk or a non-luminous RIAF.
- Luminous accretion disks are not sufficient to generate powerful radio jets.
- An additional parameter seems to be needed which may be BH spin.
- More massive galaxies (and BHs) are capable of producing higher radio power.

Summary II

- Duty Cycle is higher at lower radio powers.
- Radio activity is more frequent (longer Duty Cycle) in more massive galaxies (and BHs). This may be due to the more massive galaxies being able to sustain cooling flows which provide fuel to the BH.
- Thus, more radio mode feedback is available in the more massive galaxies where it is needed to shape the galaxy luminosity function.