The Properties of Very Powerful Classical Double Radio Galaxies

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The Sample

We consider a subset of FRII radio sources

Leahy & Williams (1984) FRII-Type I

Leahy, Muxlow, & Stephens (1989): most powerful FRII RG, $P_r(178MHz) \geq 3 \times 10^{26}\, h^{-2}$ W/Hz/sr (about 10 x classical FRI/FRII).

→ sources have very regular bridge structure

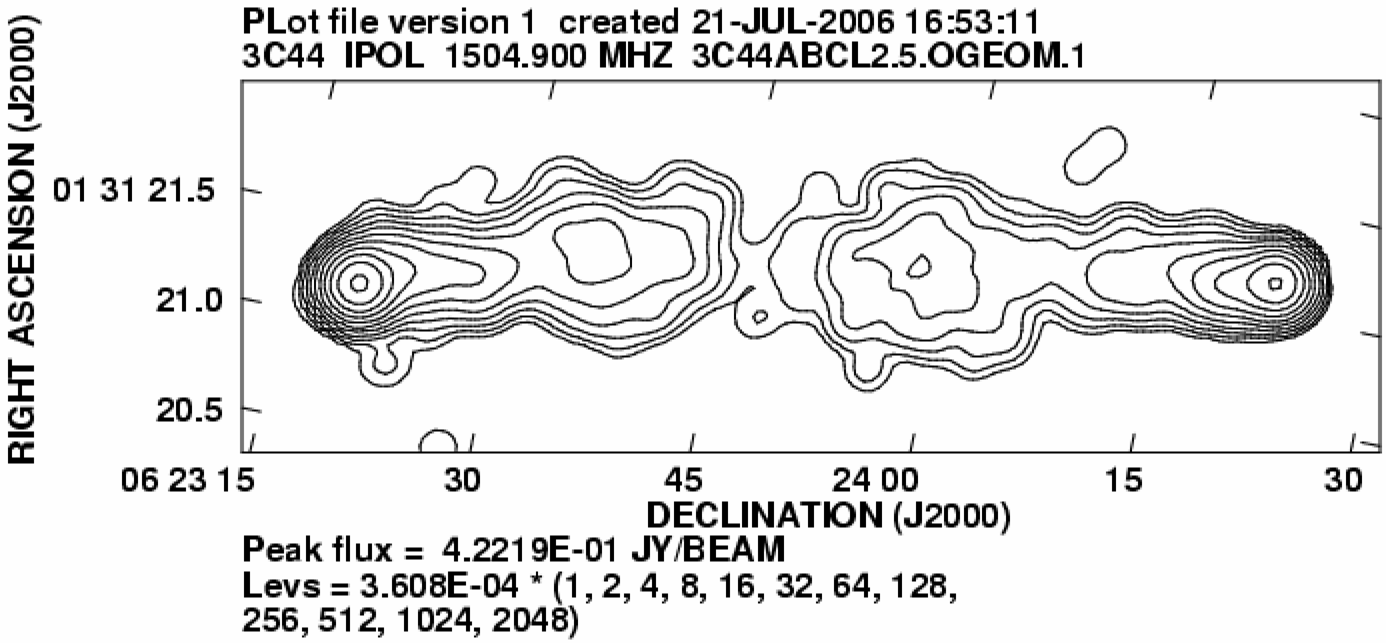
→ rate of growth well into supersonic regime

→ equations of strong shock physics apply & negligible backflow in bridge (LMS89).

→ Form a very homogenous population

& RG (not RLQ) to minimize projection effects.

For example, here is the 1.5 GHz image of 3C 44



Consider complete sample: 3CRR RG with P(178MHz) ≥ 3×10^{26} h^{-2} W/Hz/sr: → 70 RG, which form the parent population for the current study.

Recently obtained multi-frequency observations of 11 RG; combine with 9 RG from LMS89, 4 from LPR92, 6 from GDW00

→ have 30 RG with sufficient data to study source structure
z from 0 to 1.8, and D from 30 to 400 kpc

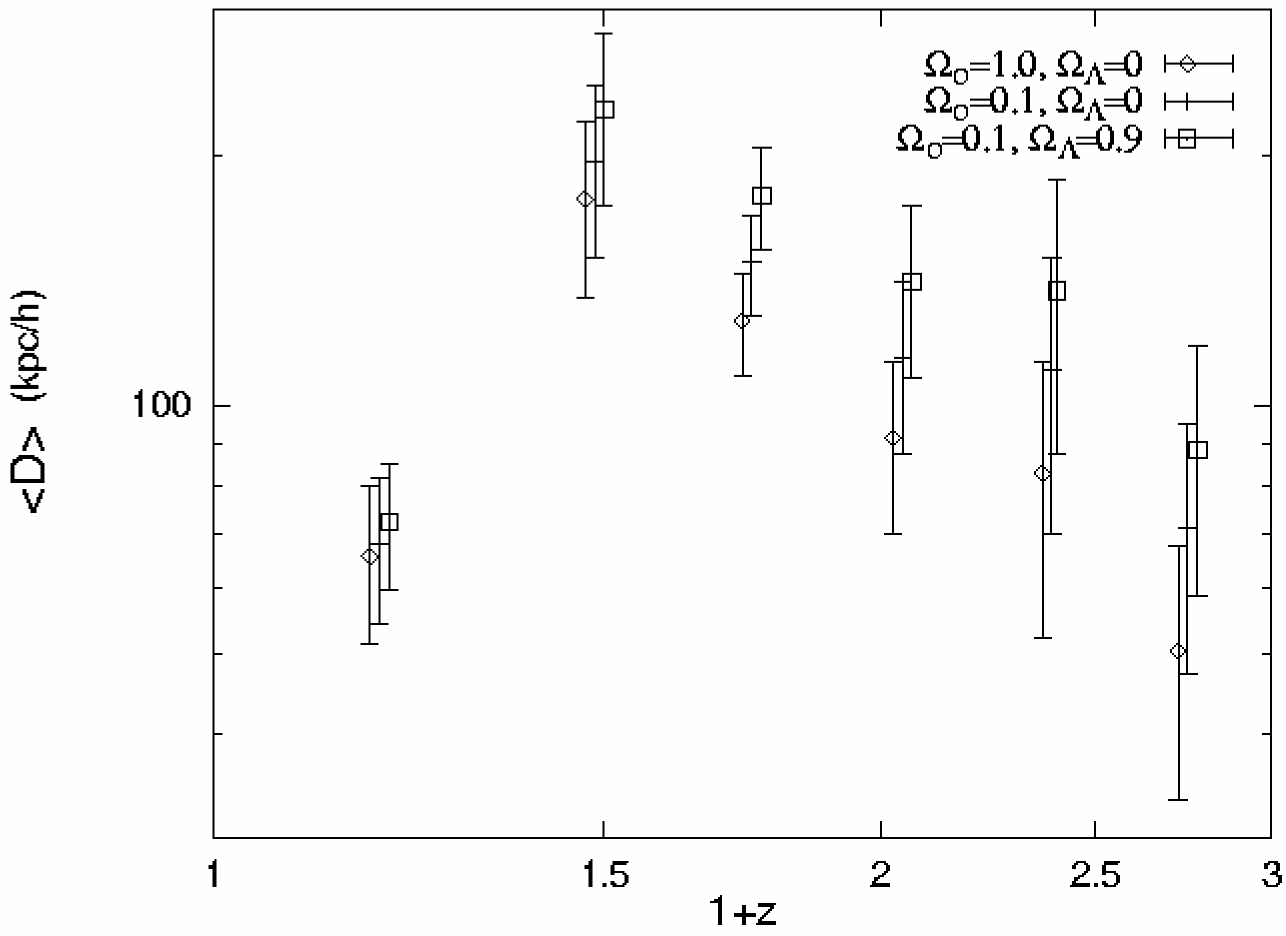
→ use data to obtain: overall rate of growth, v, along the symmetry axis of the source; the source width; and the source pressure for 30 sources (VLA time for additional 13)

Velocities determined using spectral aging analysis; recent work by Machalski et al. (2007) shows this analysis yields ages that agree with predictions in the context of a detailed model for the sources. 90 GHz observations by Hardcastle & Looney (2008) are consistent with expectations in spectral aging models. Comparisons of spectral ages with other age indicators → spectral age provides a good global parametric fit to the source age.

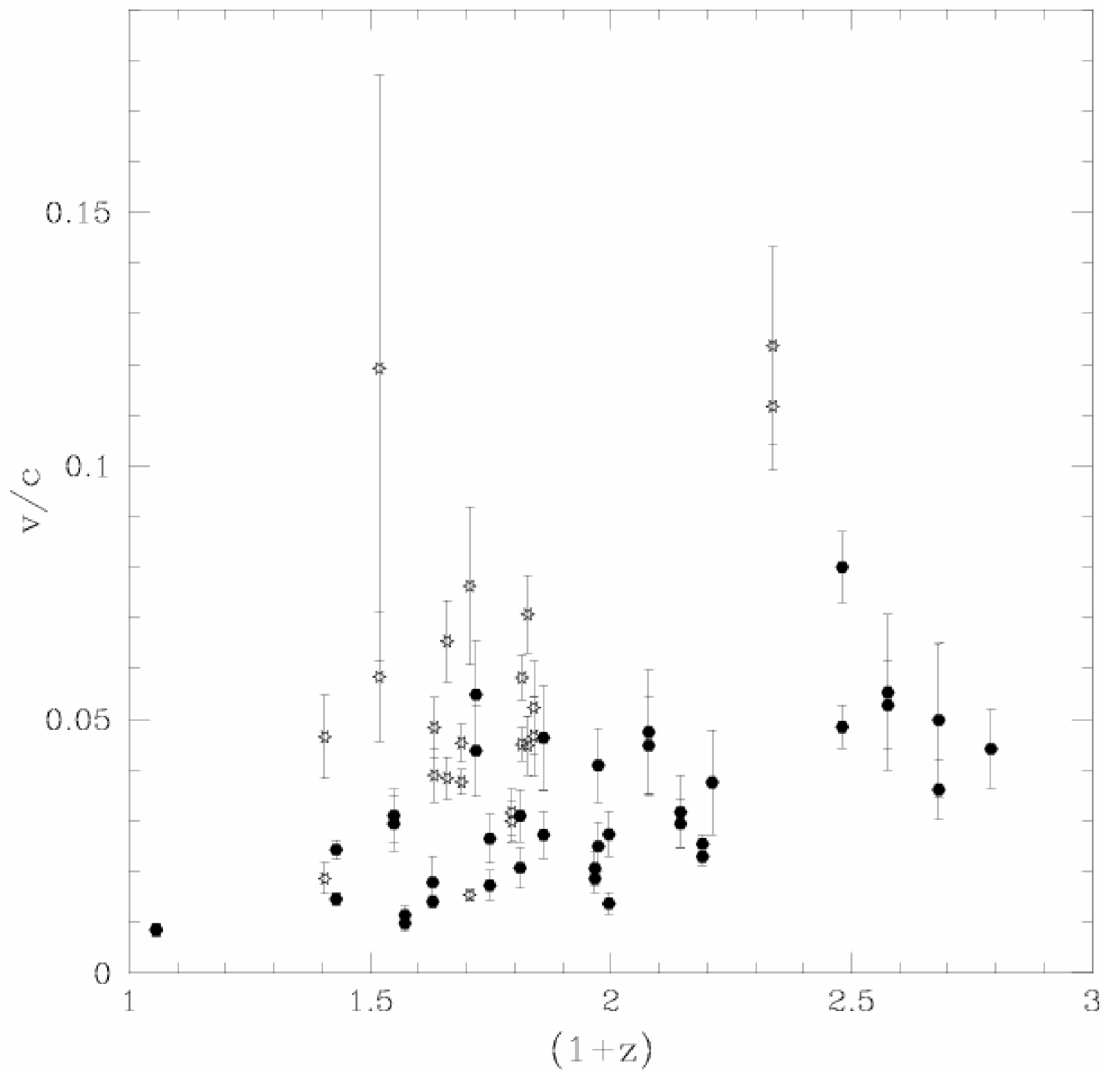
We allow for offsets of the radio emitting plasma from minimum energy conditions using $B = b\, B_{min}$; $P = [(4/3)\, b^{-1.5} + b^2]\, (B^2_{min})/24\pi$

<D> for the parent population of 70 3C Radio Galaxies with 178 MHz powers > 3 h^{-2} x 10^{26} W/Hz/sr

<D> is defined using the largest linear size



The overall rate of growth of each side of each source



The source sizes decrease systematically with z, but rate of growth of sources do not decrease with z.

We find no statistically significant correlation of v with z.

The original 20 sources are shown as solid circles, and the 11 new sources are shown as open stars.

From O'Dea et al. ('08)

Interesting and unexpected that <D> has a small dispersion at a given z and is decreasing with z for $z \geq 0.5$; source v do not decrease with z.

The studies of Neeser et al. (1995) of D, P, and z of classical doubles indicate that D and P are not correlated, but D and z are correlated.

The average size of a given source should mirror that of the parent population at that z, so $D_* \sim \langle D \rangle$. Comparing the properties of individual sources with those of parent population minimizes the role of selection effects.

The average size of a given source is $D_* \sim v\, t_*$ [t_* = total outflow lifetime]

For an Eddington limited system, $L_j \sim E_*$ (and since $t_* = E_* / L_j$) t_{EDD} would not depend upon the beam power L_j or the total outflow energy E_* ; t_{EDD} would be expected to about the same for each source. This functional form does not provide a good fit for these sources. There is little reason to expect the highly collimated relativistic outflows to be governed by a balance of radiation/outflow pressure and gravitational infall, which is the basis of t_{EDD}, especially for sources with $L_j \ll L_{EDD}$.

Generalize the relationship between t_* & L_j to be $t_* \sim L_j^{-\beta/3}$ (Daly '94)

For an Eddington limited system, $\beta = 0$, which is a special case of this more general relationship. Other paths lead to this relation.

Thus, $D_* = v\, t_* \sim v\, L_j^{-\beta/3}$

$L_j \sim v\, a^2\, P$ (from strong shock physics; applied across the leading edge)

So $D_* \sim v^{1-\beta/3}\, (a^2\, P)^{-\beta/3}$

(could also view as purely empirical relation)

This determination of the average size of a given source depends upon the model parameter β and the coordinate distance $(a_o r)$ to the source, going roughly as $(a_o r)^{-0.6}$ for our best fit β of 1.5 (after accounting for v, a, and P)

Comparing <D>, which goes as $(a_o r)$, with D_* allows a determination of β and cosmological parameters

→ require $\langle D \rangle / D_* = \kappa$ and solve for $(a_o r)$ and β; roughly **κ** $\sim$obs·$(a_o r)^{1.6}$

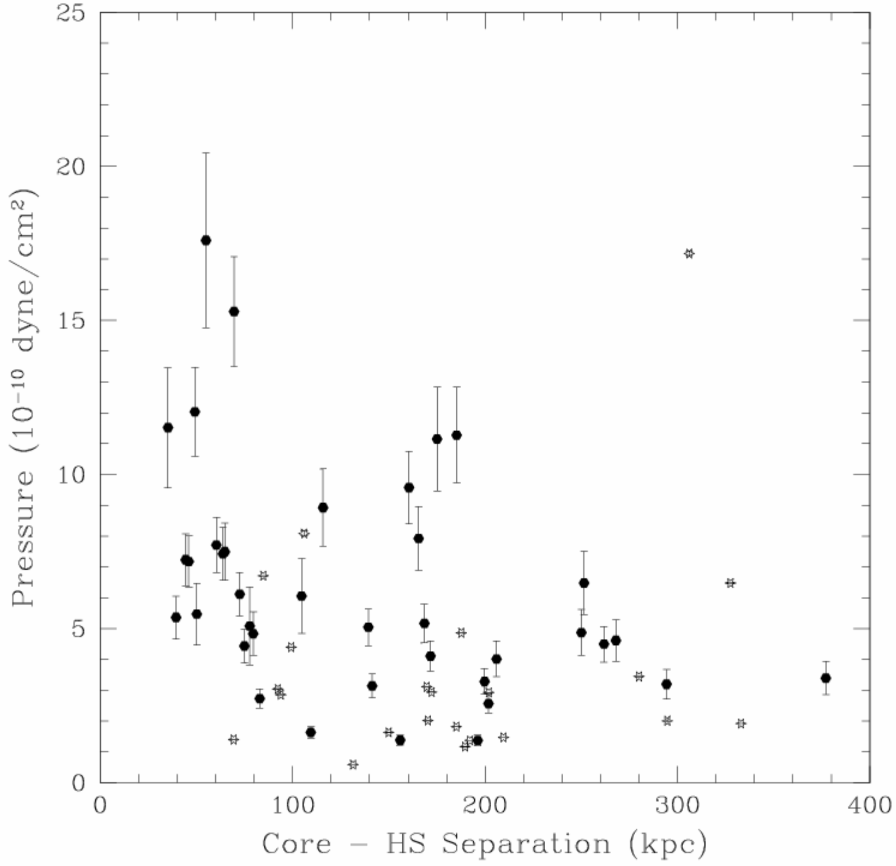
We obtain D_* for each of the 30 sources studied here and compare it with <D> for the parent population of 70 sources to solve for best fit values of β & cosm.

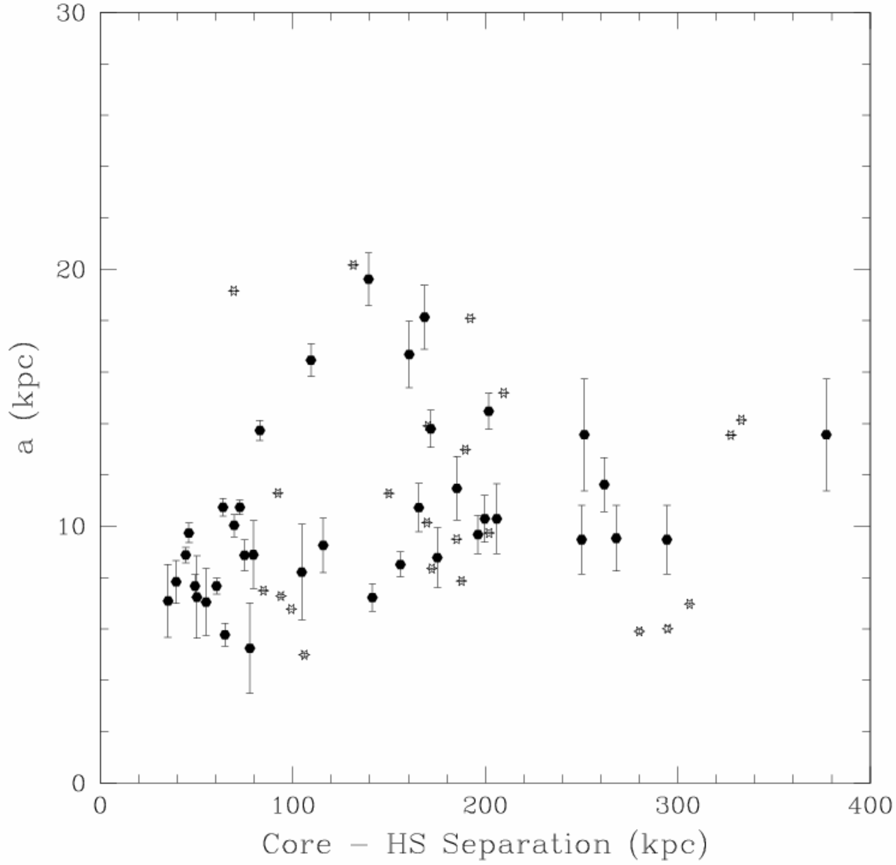
The method accounts for variations in L_j from source to source and variations in source environments (i.e. we do not make any assumptions about n_a)

Since we are comparing the properties of individual sources with those of the parent population, selection effects do not play a major role; we do not assume that any properties of the sources are constant, or pre-determined.

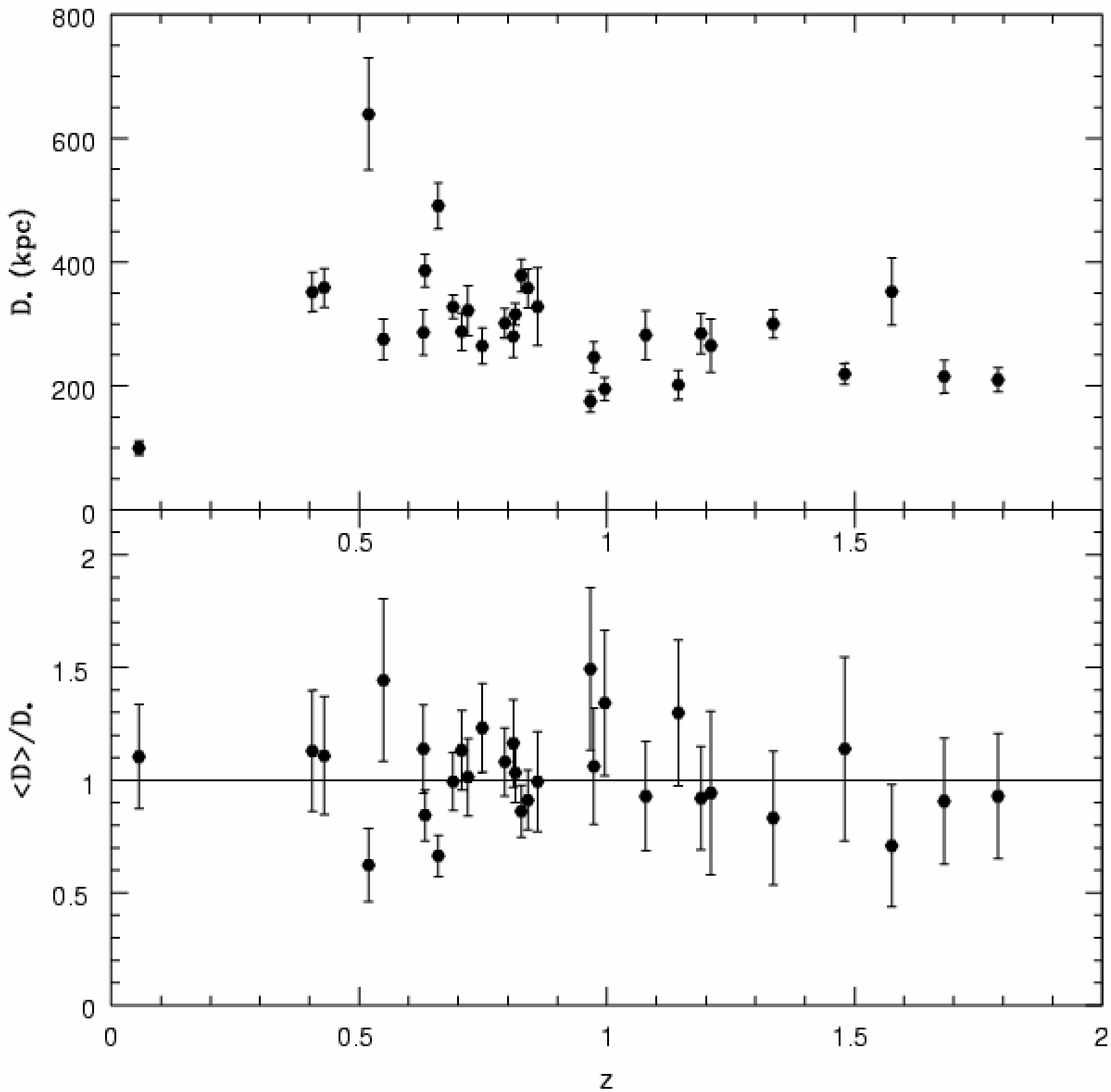
Only assumptions: $t_* \sim L_j^{-\beta/3}$, eqn. of strong shock physics apply, + v & L_j const for a given source over the source lifetime, which are consistent with obs.

Source Pressures and Widths measured 10 kpc behind the hot spot (toward the core) to obtain the time-averaged post shock conditions behind the leading edge (from O'Dea et al. 2008)





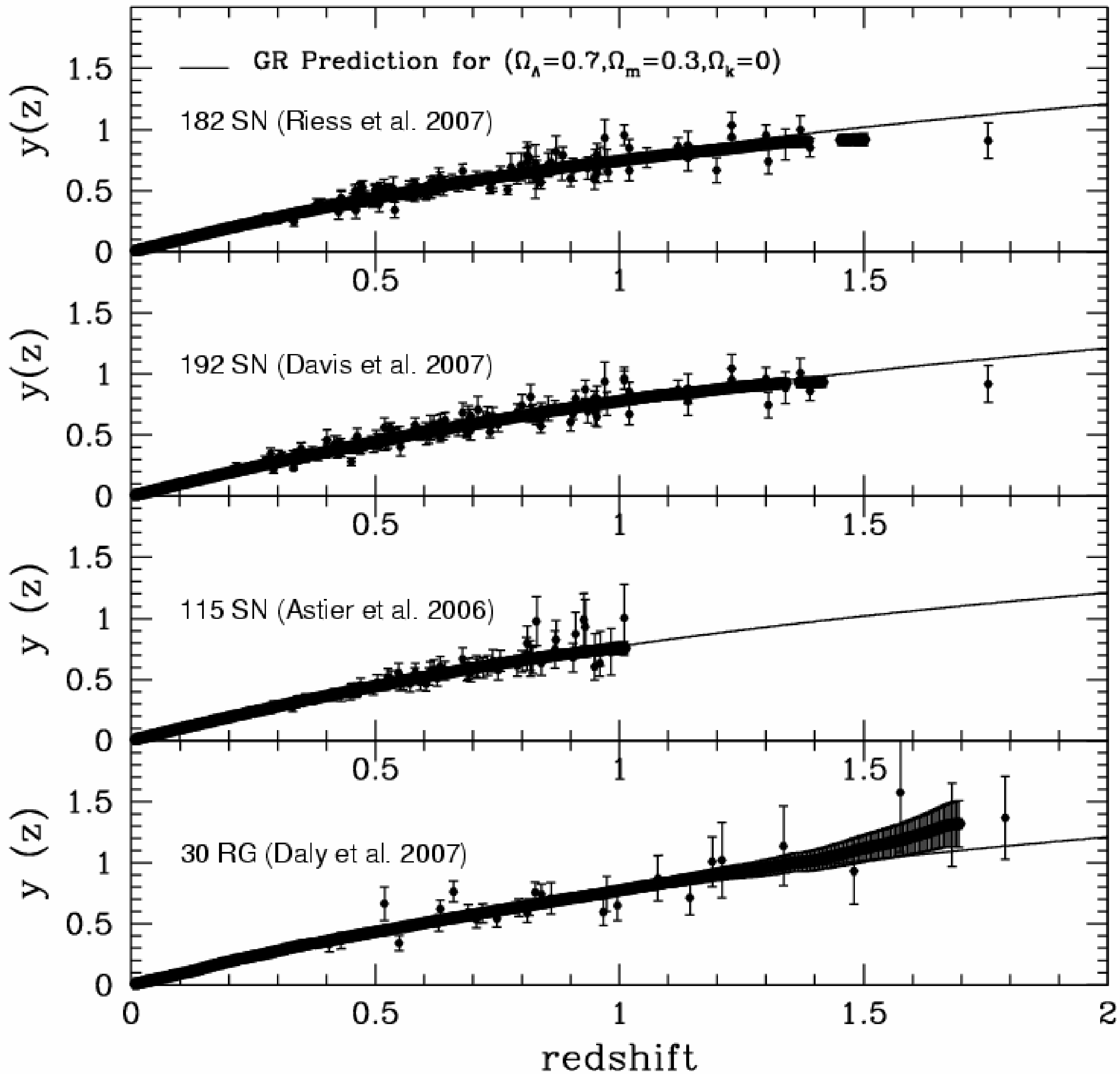
$D_* \sim v^{1-\beta/3} (a^2 P)^{-\beta/3} \sim v^{1/2} (a^2 P)^{-1/2}$ for $\beta = 1.5$



D_* shown for best fit parameters $\beta = 1.5 \pm 0.15$, $\Omega_m = 0.3 \pm 0.1$ and $w = -1.1 \pm 0.3$, obtained in a quintessence model.

The χ^2_r of the fit is about 1 (1.03)

From Daly et al. (2007)

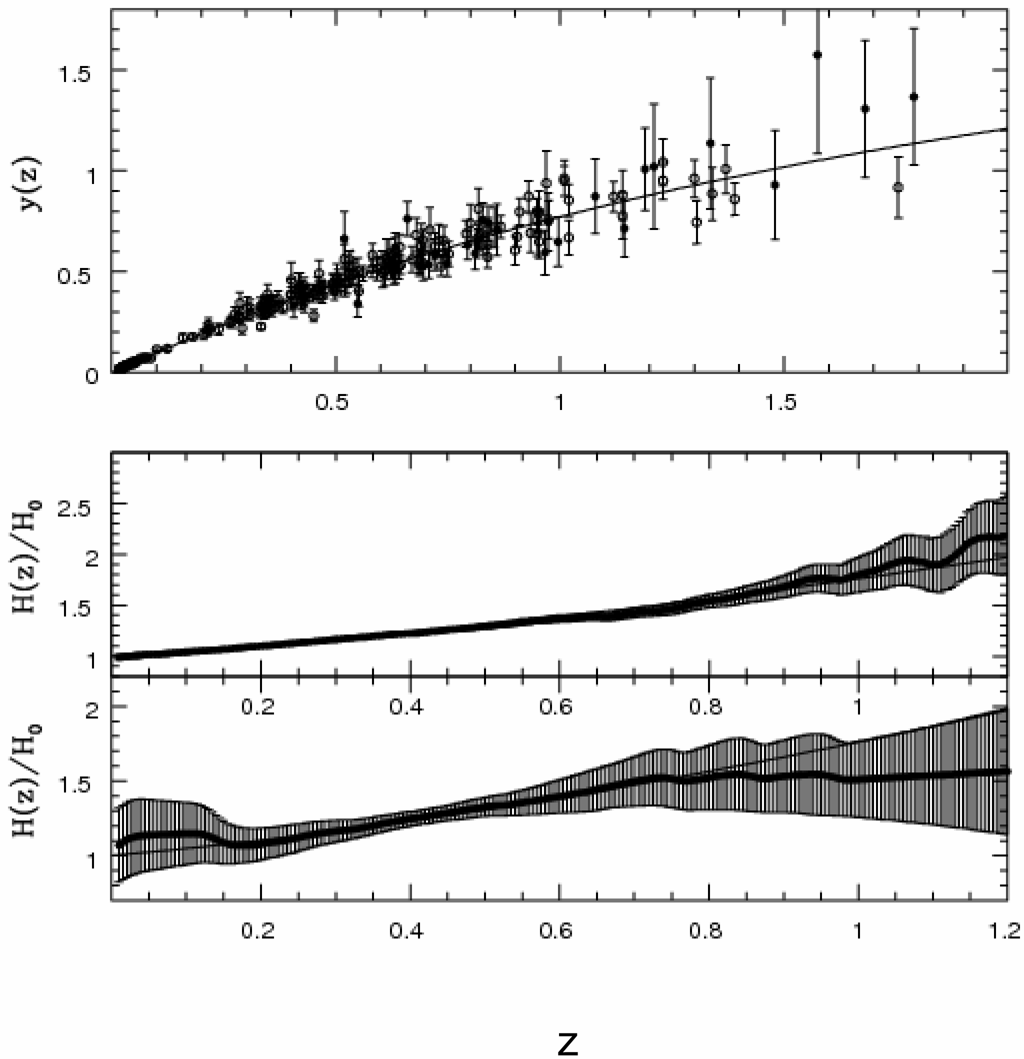


The values of <D>/D* are used to solve for the coordinate distance y without specifying a cosmological model (y is equivalent to a luminosity dist.)

There is very good agreement between SN and RG

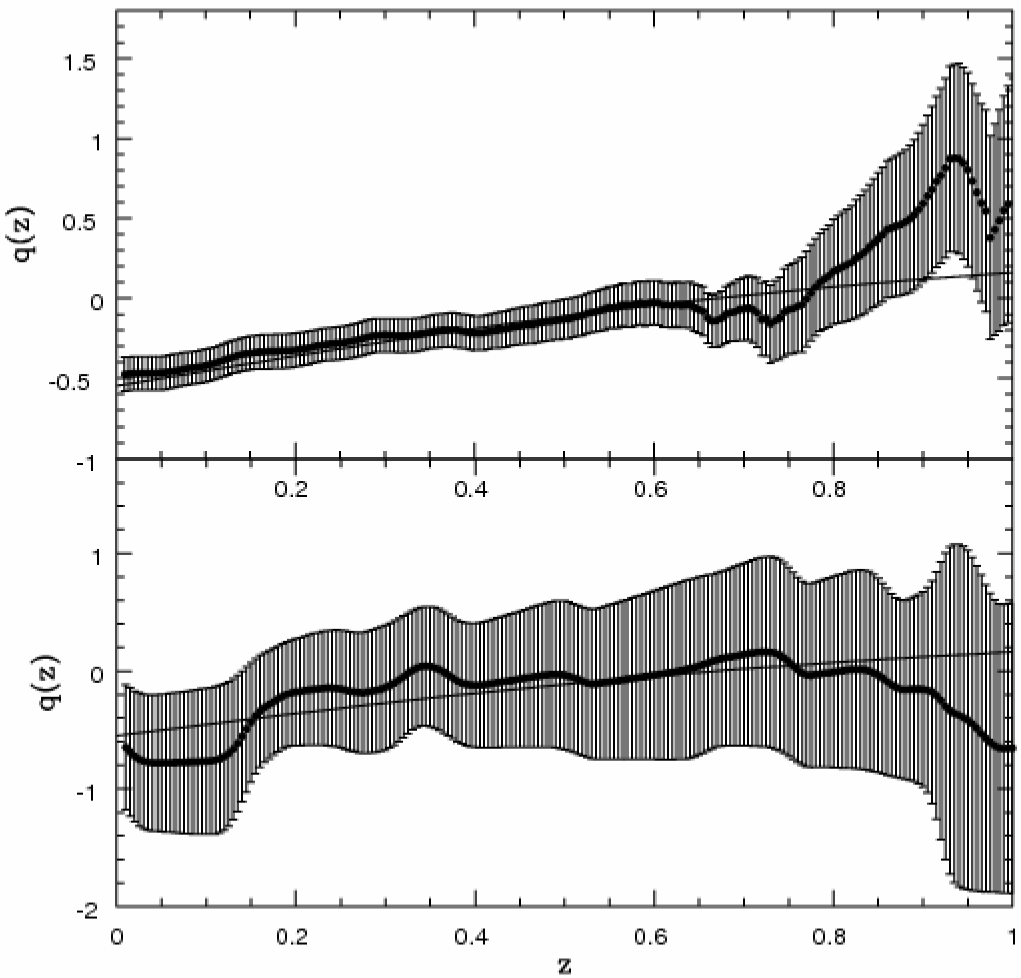
(from Daly et al. 2008)

Model-Independent Determinations of y, H, & q
(from Daly et al. 2008)



The coordinate distances, y, for RG and SN can be used to obtain H(z) and q(z) without having to specify a particular model (e.g. quintessence model); using a strictly kinematic approach. Shown here for 192SN of Davis et al. (2007) & 30 RG of Daly et al. (2007). For comparison the LCDM line for Ω_m = 0.3 is shown. Data are well described by LCDM model.

Model-Independent Determination of q(z); q_o depends only upon FRW metric; independent of k (from Daly et al. 2008)



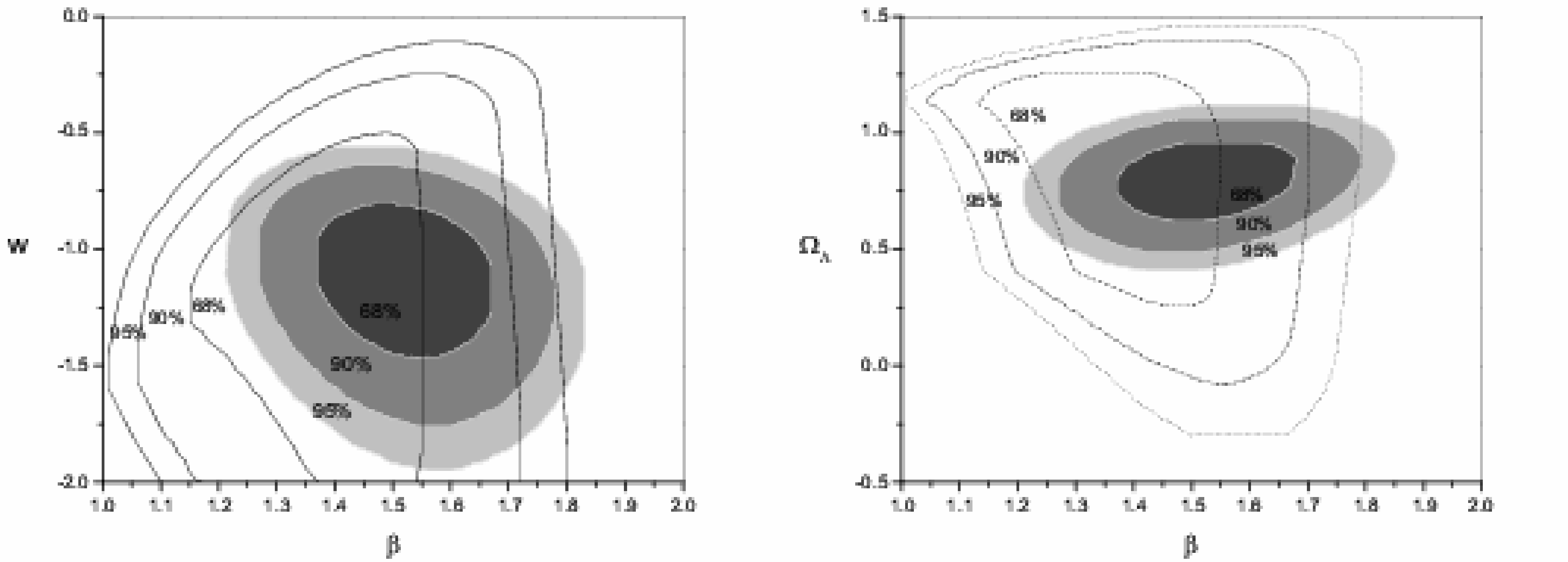
The data can be used to obtain q(z) in a completely model-independent way, using a strictly kinematic approach. Shown here for 192 SN & 30 RG; for SN find q_o = -0.48 ± 0.11 & z_T = 0.8 ± 0.2;

for 30 RG alone q_o = -0.65 ± 0.5;

Solid line is LCDM with Ω_m = 0.3

Good agreement between RG & SN

The RG model parameter β in a quintessence model for RG alone and combined 30 RG + 192 SN sample. The best fit value is $\beta = 1.5 \pm 0.15$ and there is no covariance of β with w or Ω_Λ; very similar values obtained in other models (from Daly et al. 2007).



What does our best fit value of β = 1.5 ± 0.15 suggest about the production of relativistic jets from the AGN?

In a standard magnetic braking model in which jets are produced by extracting the spin energy of a rotating massive black hole with spin angular momentum per unit mass a, gravitational radius m, black hole mass M, and magnetic field strength B, we have (Blandford 1990):

$L_j = 10^{45}\,(a/m)^2\,B_4^{\,2}\,M_8^{\,2}$ erg/s $\sim (a/m)^2\,B^2\,M^2$

$E_* = 5 \times 10^{61}\,(a/m)^2\,M_8$ erg $\sim (a/m)^2\,M$

In our parameterization, $E_* = L_j\,t_* \sim L_j^{1-\beta/3}$, which implies that

$B \sim M^{(2\beta-3)/2(3-\beta)}\,(a/m)^{\beta/(3-\beta)} \sim (a/m)$ for $\beta = 1.5$

Our empirical determination of β implies that β = 1.5 ± 0.15

This very special value of β indicates that B depends only upon (a/m) and does not depend explicitly on the black hole mass M.

It suggests that the relativistic outflow is triggered when the magnetic field strength reaches this limiting or maximum value, and is ultimately the cause of the decrease in <D> for this type of radio source.

The outflows are clearly not Eddington limited, since β = 0 is ruled out at 10σ.

The picture that emerges is: the relativistic outflow from the massive black hole is triggered when the magnetic field strength reaches a limiting or maximum value of B ~ (a/m). The value of B will be different for each BH and, since $L_j \sim E_*^2 B^2 (a/m)^{-2}$ for each BH, each BH will have $L_j \sim E_*^2$ when B ~ (a/m). The relationship indicated by our analysis is $L_j \sim E_*^2$.

When the relativistic outflow is triggered, the jet carries a roughly constant beam power L_j for a total time t_*, releasing a total energy E*. A roughly constant beam power L_j over the lifetime of a given source is consistent with the data.

The relationship between the total time the AGN is on and the beam power is $t_* \sim L_j^{-1/2}$

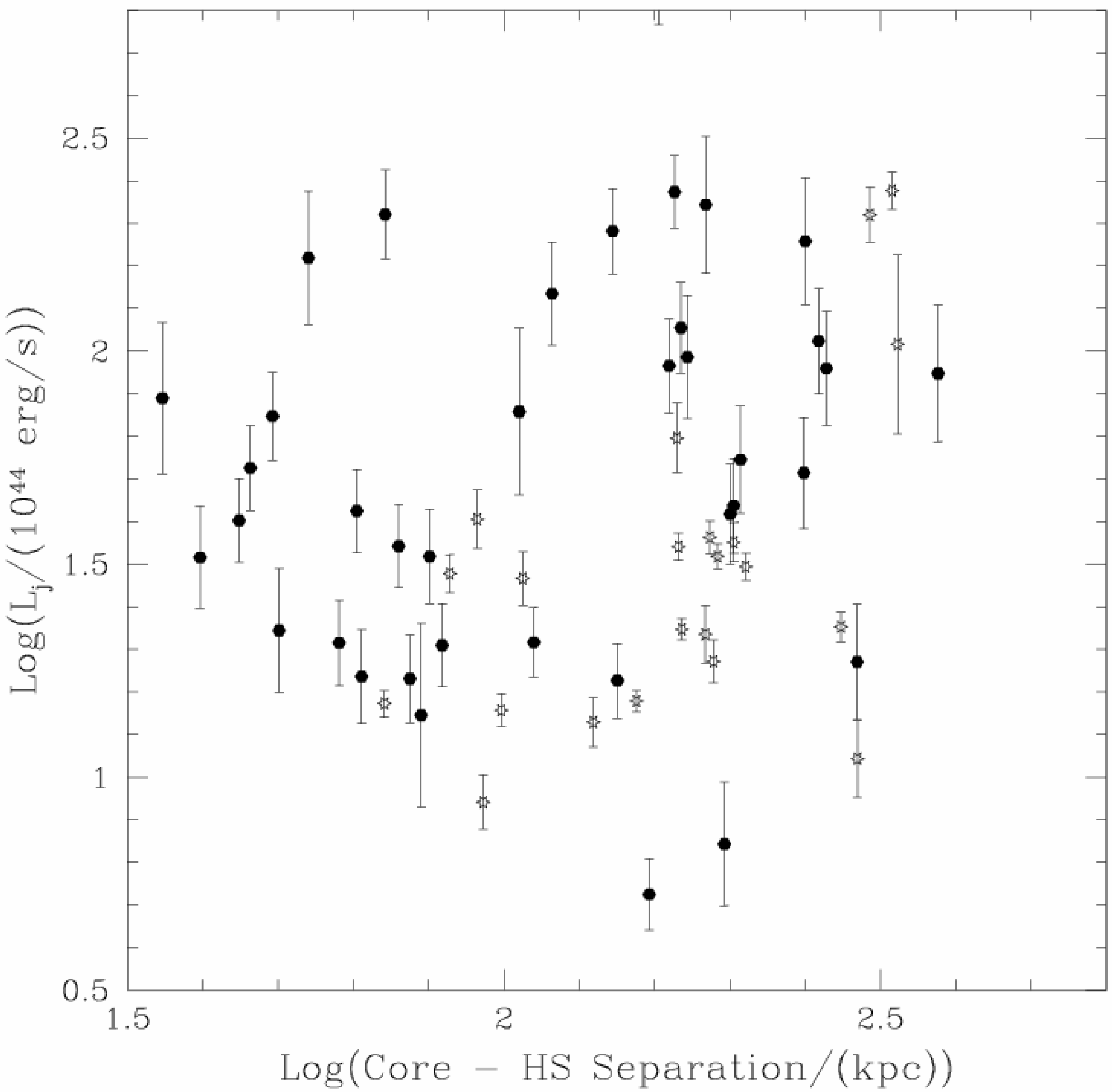
The relationship between the beam power and the total energy is $L_j \sim E_*^2$

And, the relationship between the total energy and total lifetime is $t_* \sim E_*^{-1}$

All of these relationships follow from the facts that $L_j \sim E^2$ with $E_* \sim L_j t_*$, and $L_j \sim E^2$ when B ~ (a/m).

(see Daly et al. 2007 for details)

The Beam Power $L_j = dE/dt \rightarrow$ the source



L_j is obtained by applying the strong shock equation:

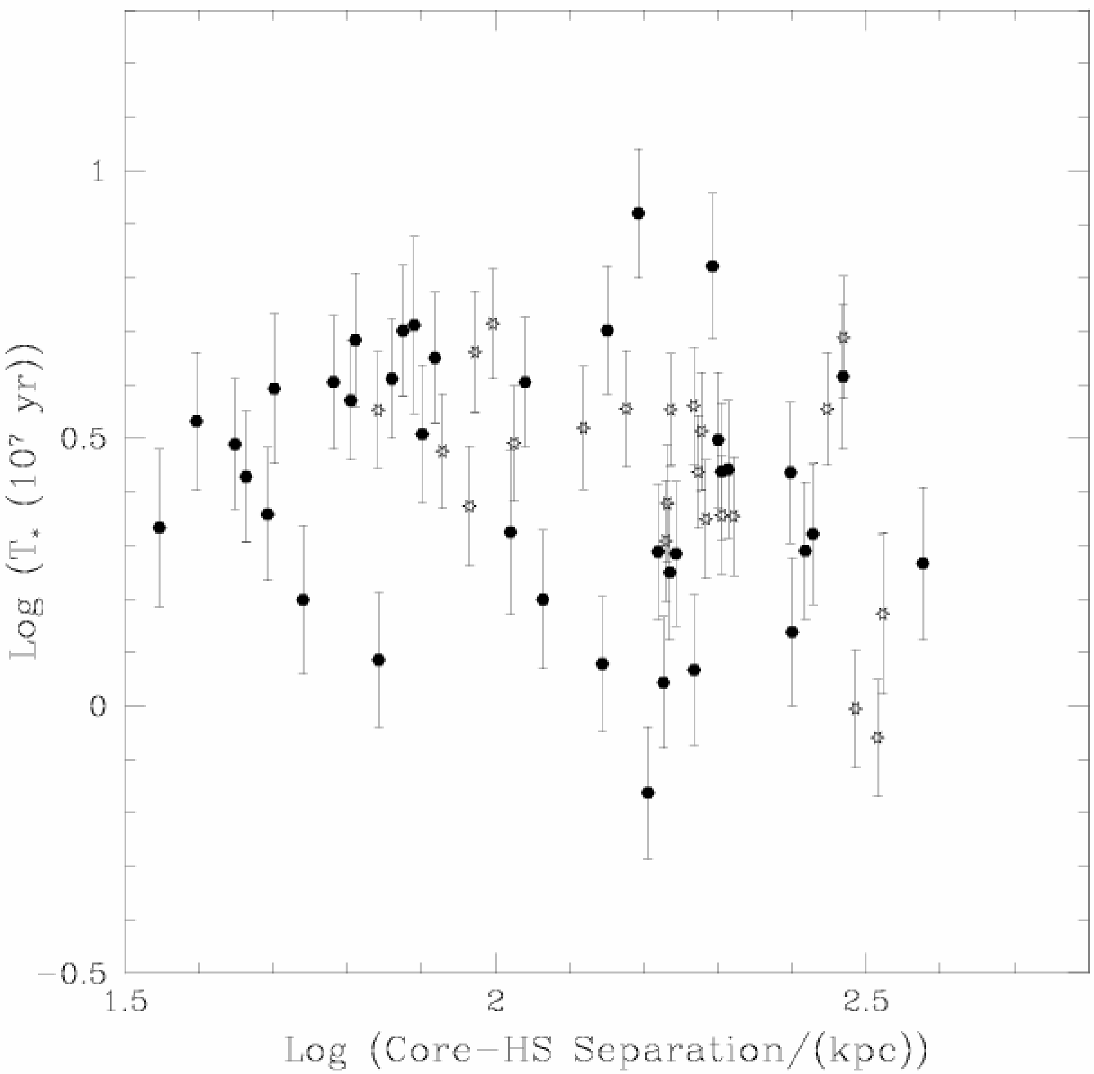
$L_j = a^2 P v$

Find no correlation between L_j & D

L_j obtained here is independent of offsets from minimum energy conditions due to the cancellation of B in v and P (O'Dea et al. 08)

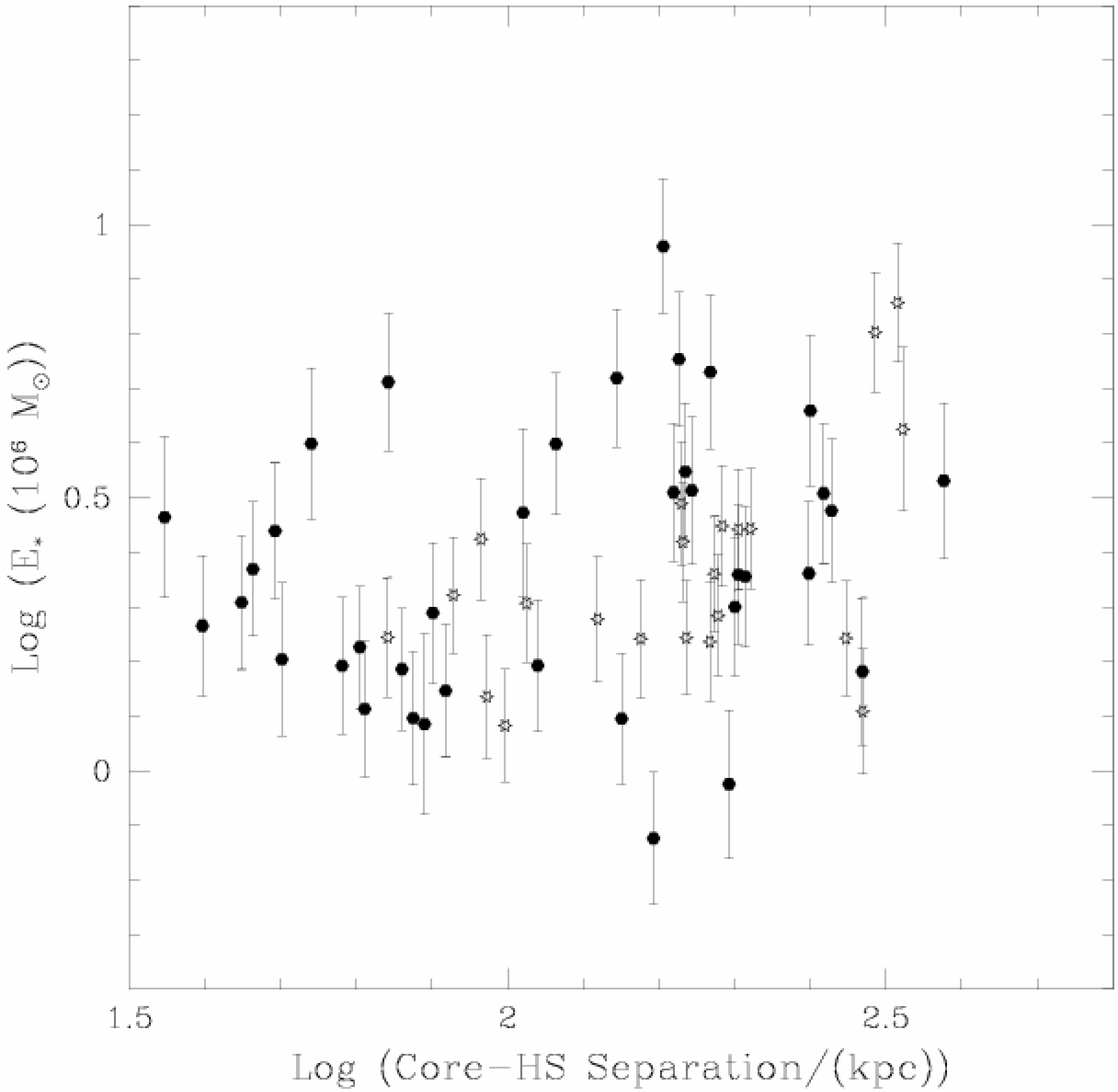
$L_{EDD} = 10^{47} M_9$ erg/s so all of these L_j can have $L_j \ll L_{EDD}$

Total source lifetime determined from $t_* \sim L^{-1/2}$



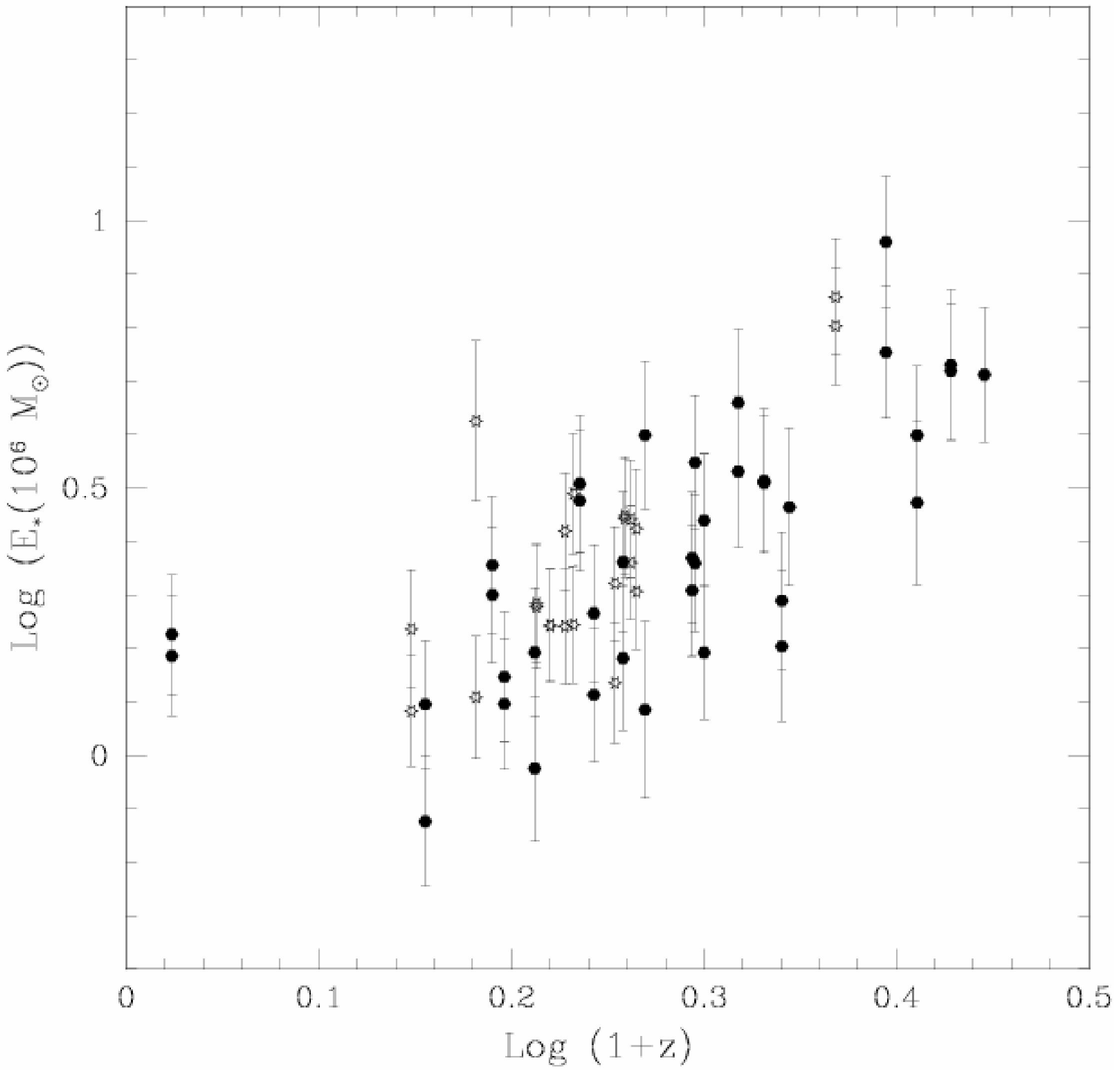
The fact that t_* is independent of D indicates that our determinations T_* are not biased by the epoch at which we observe a particular source, and that we are randomly sampling sources during their lifetimes.

Total Energy $E_* = L_j \, t_* \sim L_j^{1/2}$



The fact that E_* is independent of D indicates that our determinations of E_* are not biased by the epoch at which we observe the source.

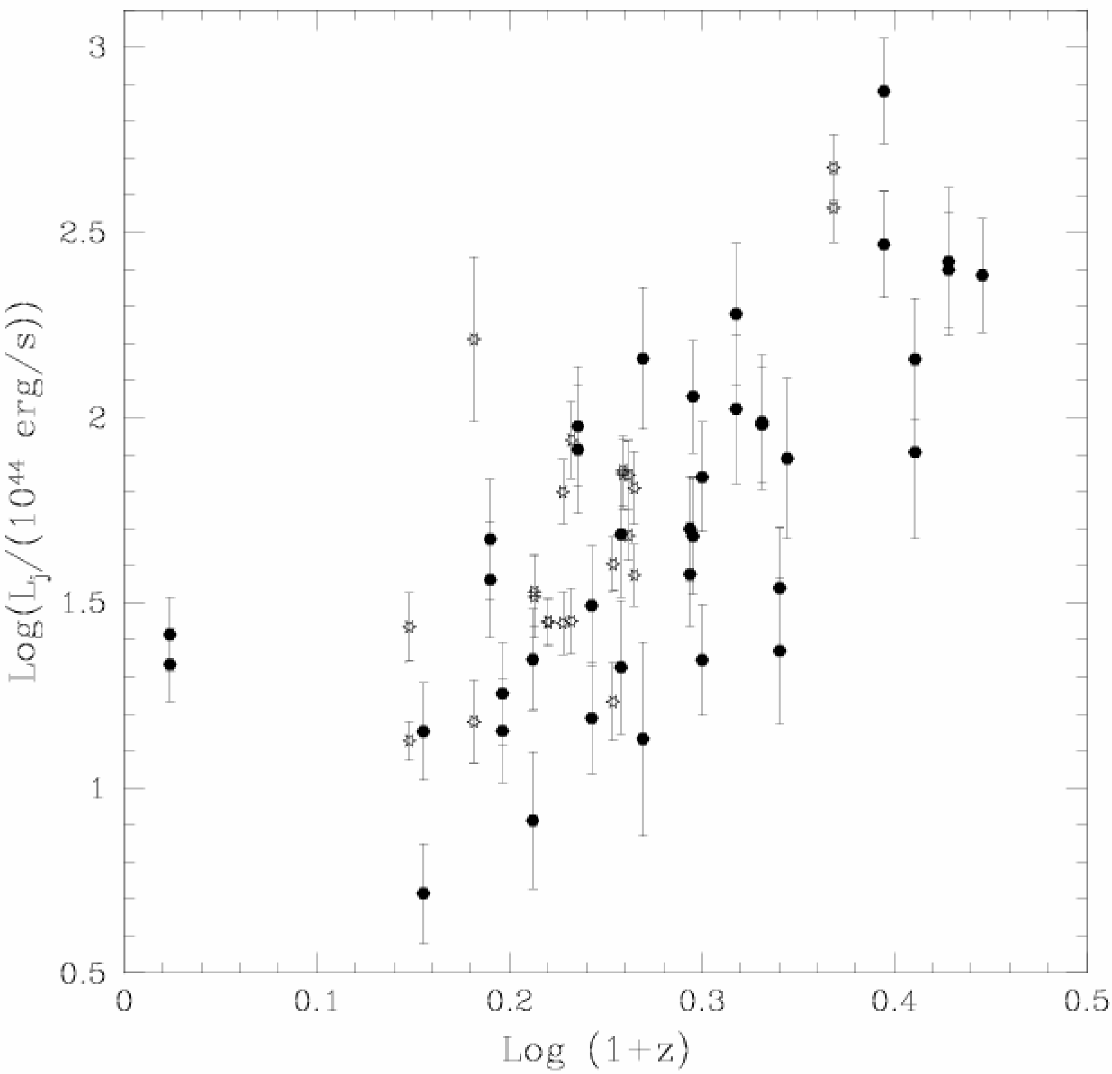
Total Energy $E^* = L_j \ t^* \sim L_j^{1/2}$



$E_* \sim (a/m)^2 M$

So the ↑ of E_* with z indicates that (a/m) or M is higher for higher z sources, that is, the very high (a/m) or M sources are active at high z but not low z.

Beam Power L_j from $L_j = P\ v\ a^2$



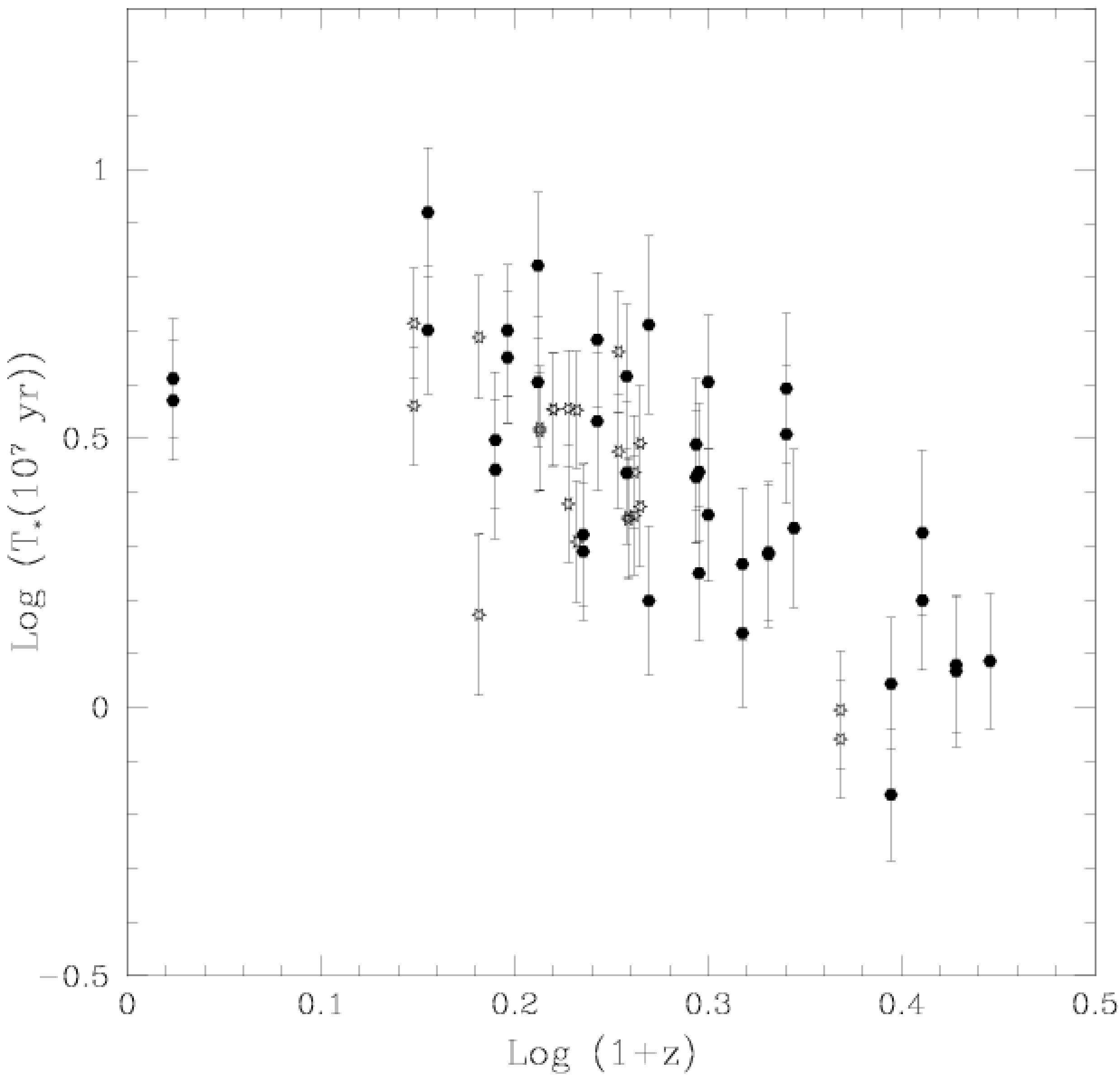
L_j ↑ by 2 orders of magnitude.

At a given z, L_j has a range of an order of magnitude.

These determinations of L_j are independent of offsets of the B field from minimum energy conditions [O'Dea eta. 07]

$L_j \sim (a/m)^2\ B^2\ M^2$ and $B \sim (a/m)$ so $L_j \sim (a/m)^4\ M^2$ is ↑ with z bec. (a/m) or M ↑ with z

$t_* \sim L_j^{-1/2}$; $t_* = E_*/L_j \sim B^{-2} M^{-1} \sim (a/m)^{-2} M^{-1}$ for $B \sim (a/m)$

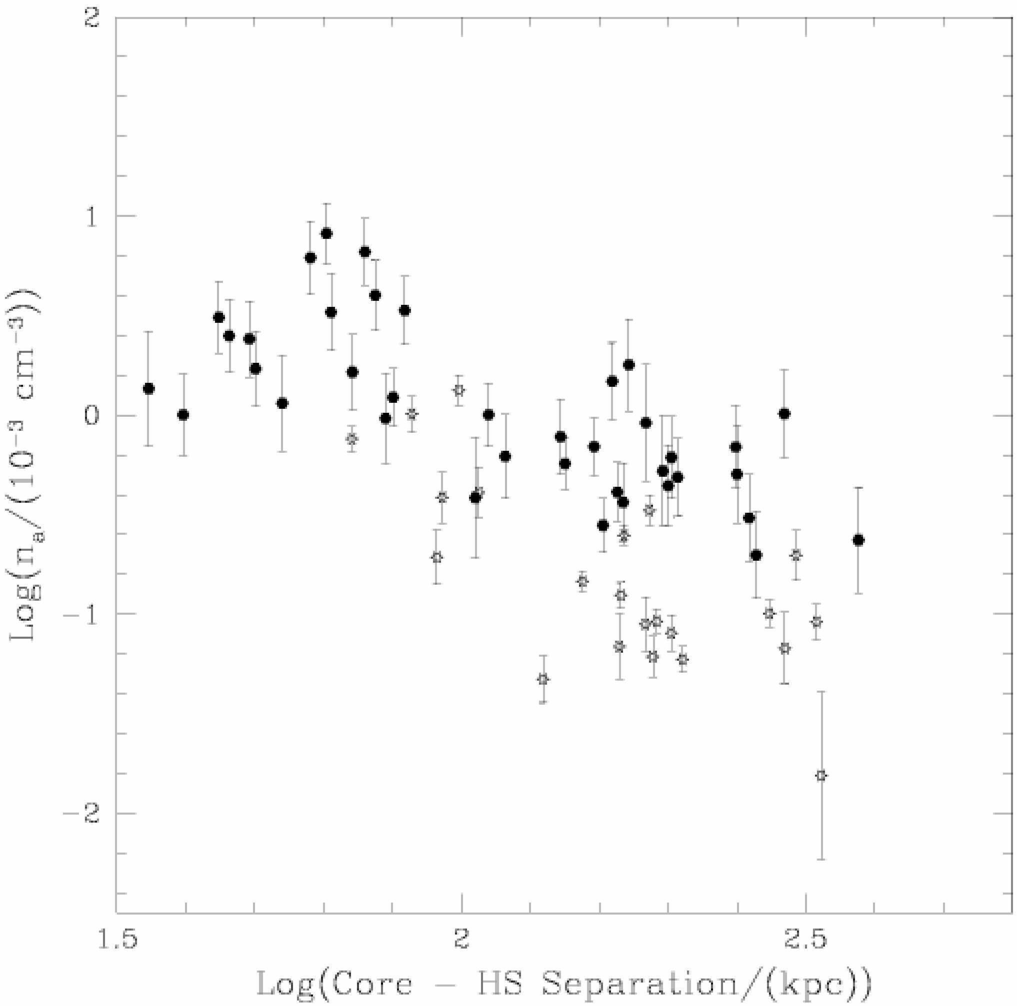


Higher z sources in the sample studied have higher L_j and E_* than the lower z sources studied, and thus have shorter lifetimes and smaller sizes.

This is consistent with the lack of any observed relation between P and D for these sources.

There is no need to demand that all sources have the same lifetime, because the outflow is unrelated to L_{EDD}.

The ambient gas density n_a



The ambient gas density is obtained using the equation of ram pressure confinement

$n_a \sim P/v^2$

$n_a \sim D^{-1.9 +/- 0.6}$

As expected for these values of D

(from O'Dea et al. 2008)

No assumptions about the source environments are made to obtain β and cosmological parameters.

Consistent with Croston et al. (2005) & Belsole et al. (2007).

Summary

With the very simple relations, $D_* = v\ t_*$, $t_* \sim L^{-\beta/3}$, and applying the strong shock relation $L \sim v\ a^2\ P$ near the forward region of the shock, we can solve for the model parameter β and cosmological parameters; no assumptions are made about the source environments or beam powers.

The cosmological parameters we determine are in very good agreement with those obtained by independent methods, such as the type Ia SN method.

The model parameter β can be analyzed in a standard magnetic braking model, and the value we obtain is a very special value, $\beta = 1.5 \pm 0.15$, which implies that $B \sim (a/m)$ for each source.

This leads to a picture in which the collimated outflow is triggered when B reaches this limiting or maximum value, producing jets with roughly constant L_j over their lifetime t_*, and $t_* \sim L_j^{-1/2}$, $t_* \sim E_*^{-1}$, and $L_j \sim E^2$.

The outflows are unrelated to the Eddington luminosity, and have beam powers well below L_{EDD}; there is no need to require that each source produces an outflow for the same total time.

More coming soon….we have VLA time to study another 13 sources