Chandra Observations of Classical Double Radio Galaxies in Nearby Brightest Cluster Galaxies

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15 Years of Science with Chandra (Boston MA, 18-21 Nov 2014)

“Radio-mode” feedback

- Temperature and entropy profiles of hot gas in galaxy clusters, groups, and isolated ellipticals
- Suppressed starformation in (high-z) galaxies in formation
- Regulated growth of SMBHs over cosmological timescales

-> Interactions of relativistic jets with their environment!

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-> Interactions of relativistic jets with their environment!

- Brightest Cluster Galaxies (BCGs) are more likely radio-loud
- AGN jets are in principle powerful enough to do the job (unlike AGN disk winds)
- Jet-related feedback can account for suppressing the starformation without itself requiring starformation (unlike starburst-related feedback; Croton +06)

How does it work?

- Expected strong shocks driven in the surrounding medium by the expanding jet cocoons/lobes (Clarke +97, Heinz +98, Kaiser & Alexander 99)
- …but no signatures of such have been found in the first high-resolution Chandra exposures… This led to the idea of
- Transonic expansion of short-lived lobes, rising in the cluster atmosphere in a form of buoyant bubbles, converting ***somehow*** their enthalpy to the gas kinetic energy (e.g., Churazov +01, Fabian +03, Ruszkowski +04)

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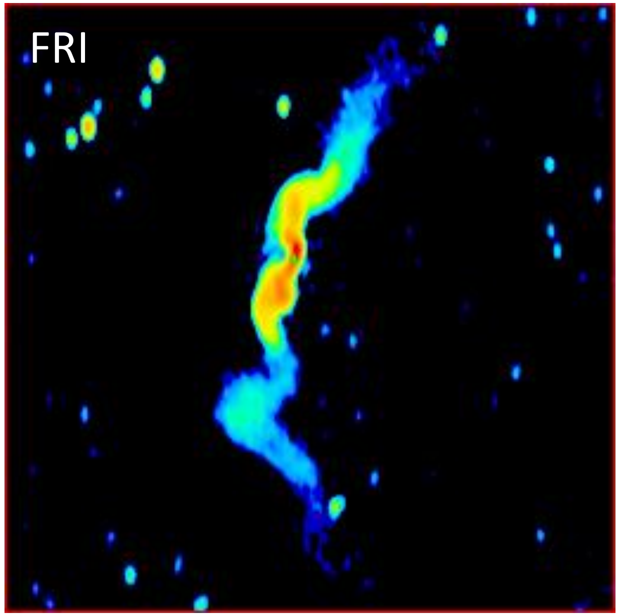
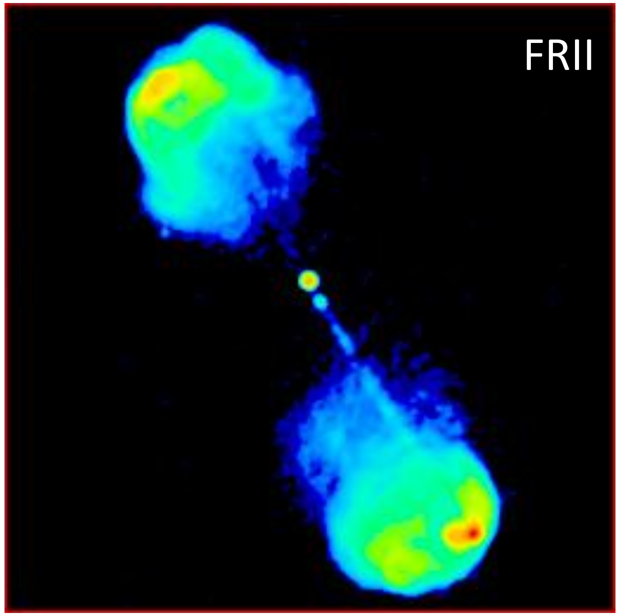
However…

- Details of the related energy dissipation processes quite controversial
- Stability of buoyant bubbles in the ICM quite problematic (e.g., Jones & De Young 05, Diehl +08, O'Neil +09)
- Weak shocks associated with large-scale lobes in galaxy clusters finally found in deep Chandra and XMM-Newton exposures of various systems

  (McNamara +05, Gitti +07, 11, Nulsen +05a, 05b, Fabian +06, Wise +07, Simionescu +07, 09, Forman +05, 07, Wilson +06, Reynolds +08, Cavagnolo +11, Blanton +11, Lal +10; also Kraft +07, Croston +07, 09, Jetha +08, Gitti +10, Randall +11, Siemiginowska +12, Shelton +11)

FRI versus FRII radio sources





- FRII radio sources are on average more luminous in radio than FRIs; large-scale morphologies of their radio lobes are consistent with a supersonic expansion, in contrast to the (trans)-sonic expansion of FRI-type plume structures
- At lower redshifts FRIIs seem to avoid dense cluster environment
  (e.g., Wan & Daly 96; Zirbel 97; Harvanek & Stocke 02; Slee +08; Wing & Blanton 11)
- At higher redshifts, however, FRIIs are found also in rich systems
  (e.g, Yates +89; Hill & Lilly 91; Siemiginowska +05; Belsole +07; Antognini +12)

Why should we care about FRIIs?

- Long-term evolution of FRIIs ("classical doubles") is very well understood, and tested in many different numerical simulations (Begelman & Cioffi 89, Kaiser & Alexander 97, Komissarov & Falle 98), unlike the long-term evolution of FRIs…
- Local luminous FRIIs may be more representative for the high-z universe than weak FRIs
- Efficient heating of the ICM, suppression of the starformation in the evolving galaxies, or regulating the SMBH growth, requires powerful jets of the FRII type, with $L_j \geq$ 1e45 erg/s and $t_j \geq$ 10 Myr (Voit & Donahue 05, Matthews & Guo 11, Antognini +12)

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One should keep in mind that

- FRI/FRII division based on the total radio power (Fanaroff & Riley 74), or radio power as a function of the optical luminosity of the host (Ledlow & Owen 96), is not really strict
- The often anticipated unification of FRI/FRII radio sources with LERGs/HERGs (Laing +94) is not really exact
- The common assumption that FRII nuclei are associated with standard Shakura-Sunyaev disks ($L_{acc}/L_{Edd} > 0.01$) while FRIs with radiatively inefficient accretion flows ($L_{acc}/L_{Edd} < 0.01$), may in many cases be quite misleading

FRIIs at the centers of galaxy clusters

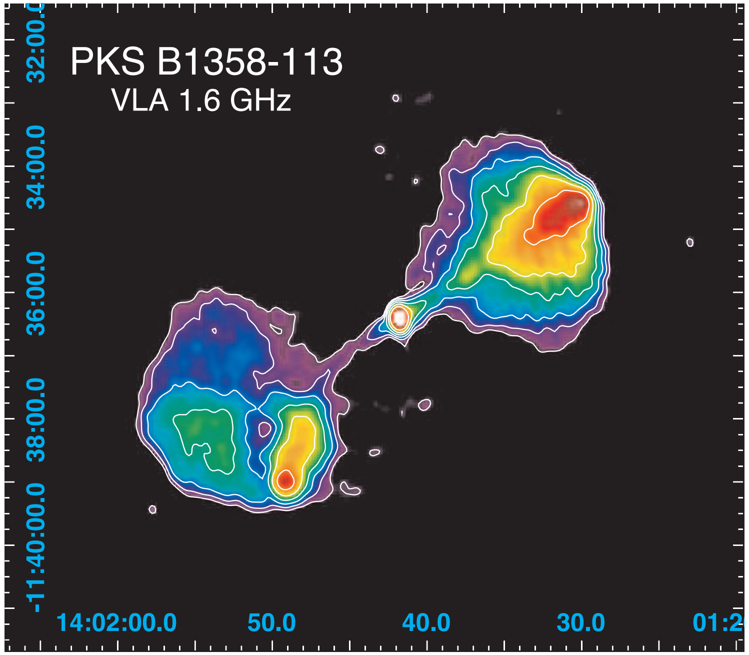
- Common at high redshifts, but then hardly accessible for detailed multiwavelength studies; at low redshifts only a few examples known (e.g., Cygnus A)
- We examined the NRAO VLA imaging survey of Abell clusters with $z < 0.25$ and $R \geq 0$ (Owen +92, Owen & Ledlow 97), and found only two FRIIs hosted by the BCGs (out of 400 systems): PKS B1358-113 in A1836 ($z=0.0363$, $R=0$), and 4C+67.13 in A578 ($z=0.0866$, $R=0$).
- We have analyzed all the archival VLA data for the two selected systems, performed their optical spectroscopy using the William Herschel Telescope, and gathered the high-quality X-ray data with the XMM-Newton and Chandra satellites.

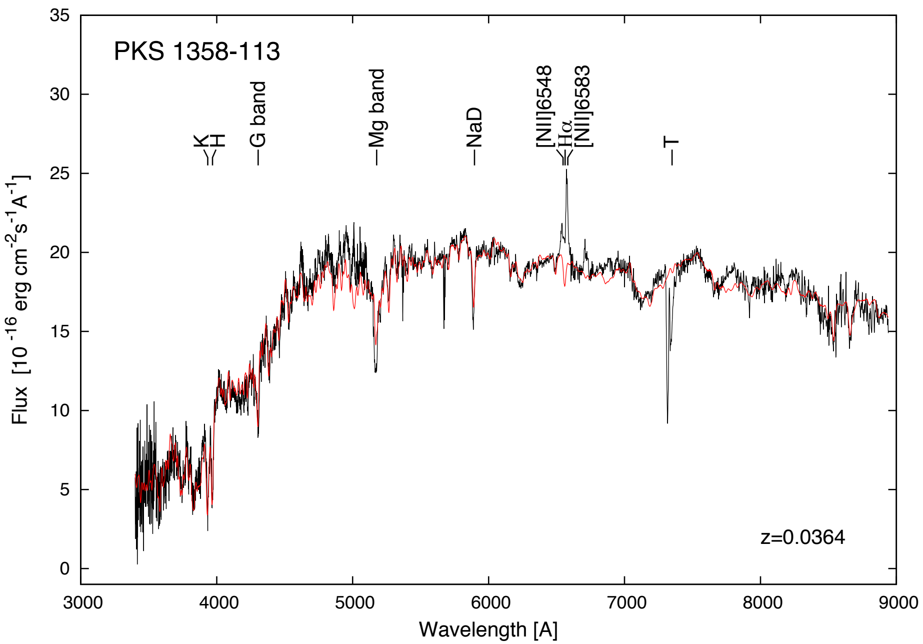
The Results:

Stawarz et al. 2014, ApJ, 794, 164 (for PKS B1358-113/A1836)

Hagino et al. 2014, ApJ, submitted (for 4C+67.13/A578)

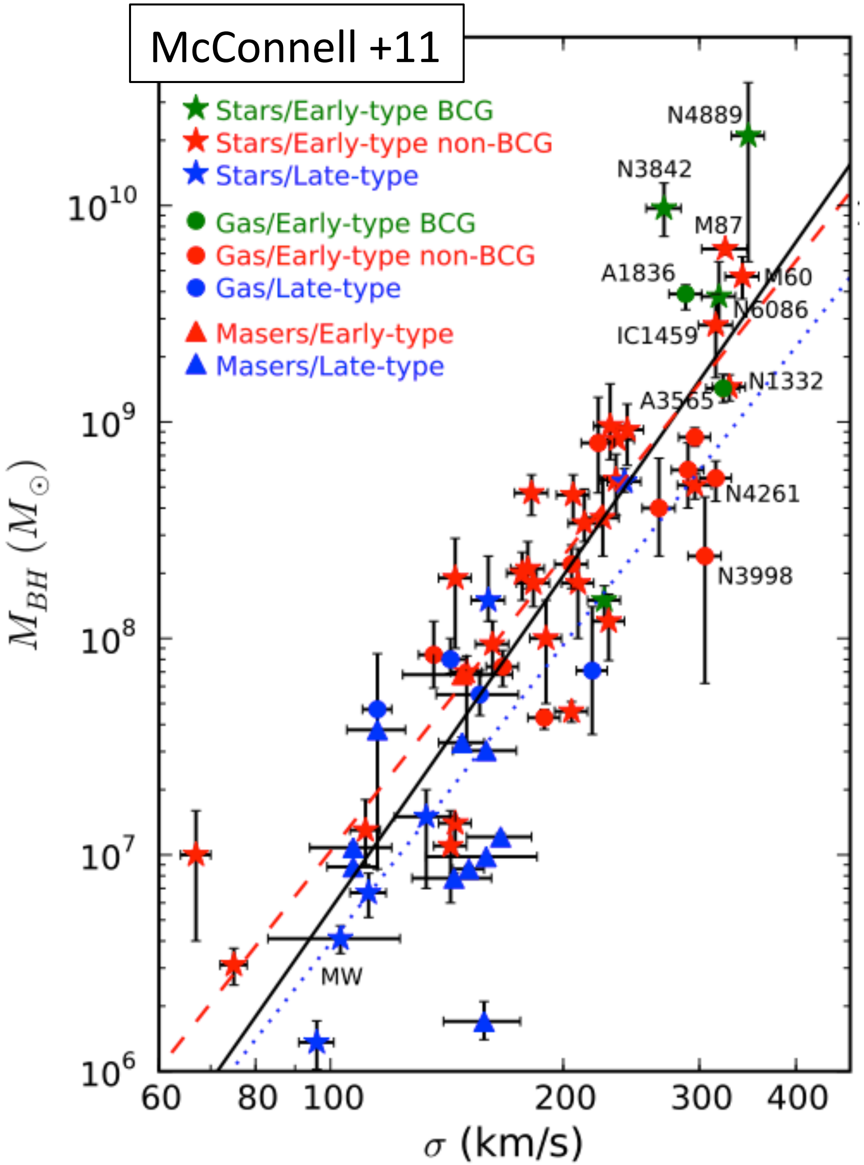
PKS B1358-113/A1836

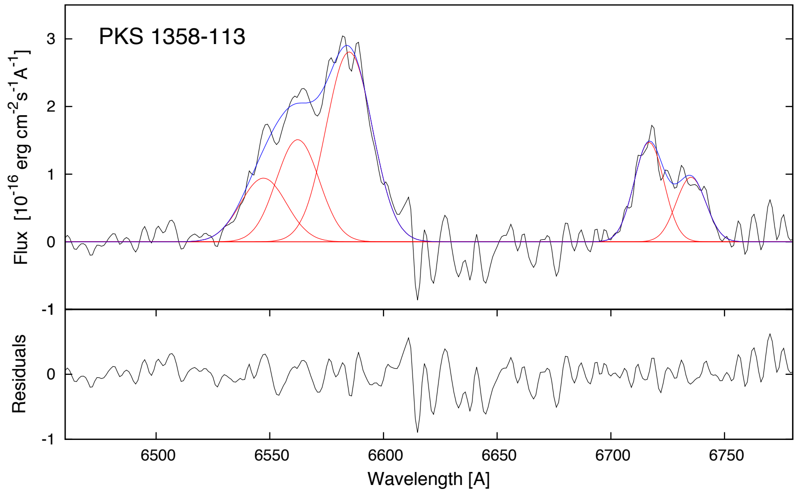




- Classical FRII radio morphology; radio power $L_{1.4GHz}$ = 8e40 erg/s below the FRI/FRII division (host magnitude M_R=-23.0)
- Elliptical host with a mixture of 1Gyr and 10Gyr stellar populations, with no trace of young (<Gyr) stars (fit using the STRALIGHT code; Cid Fernandes +05)
- Velocity dispersion σ=295.0±6.0 km/s

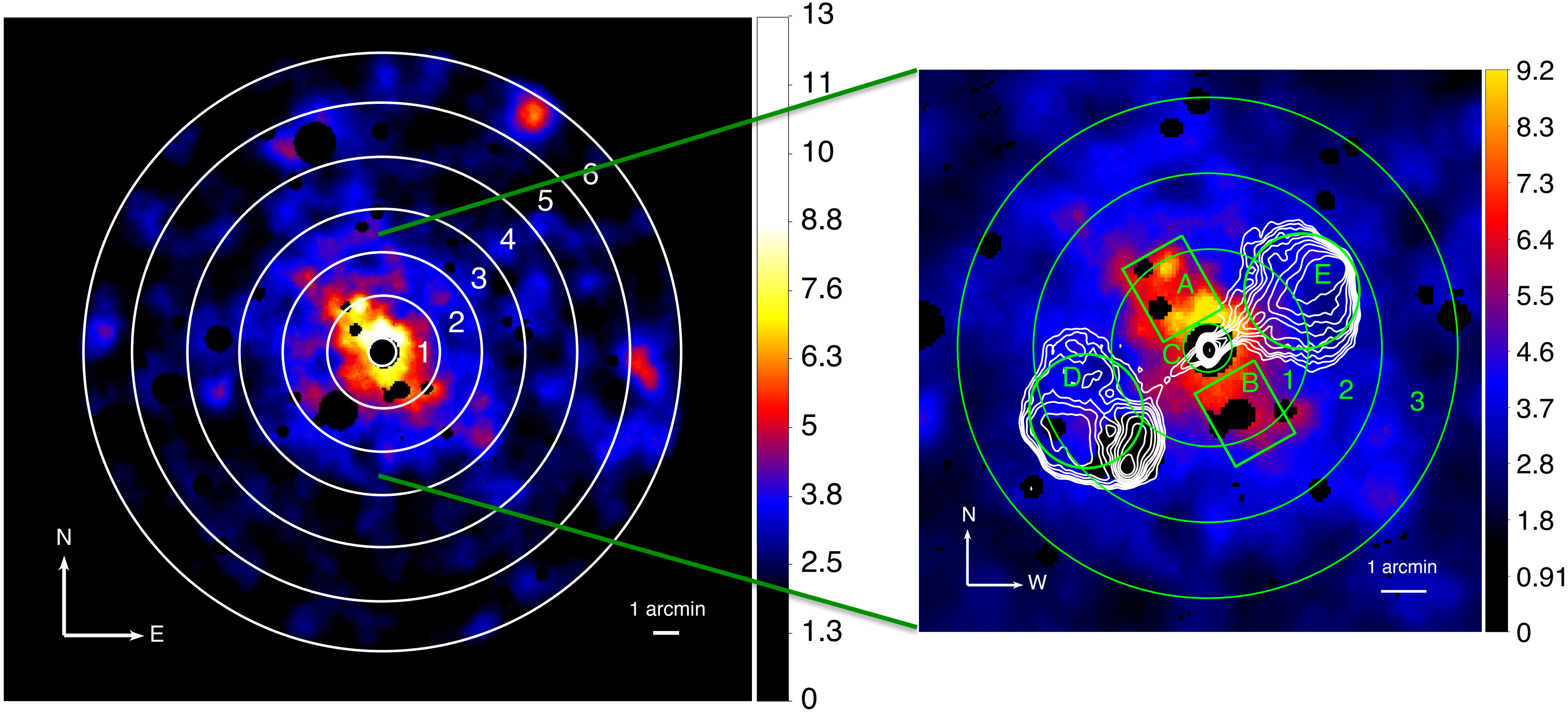
PKS B1358-113/A1836





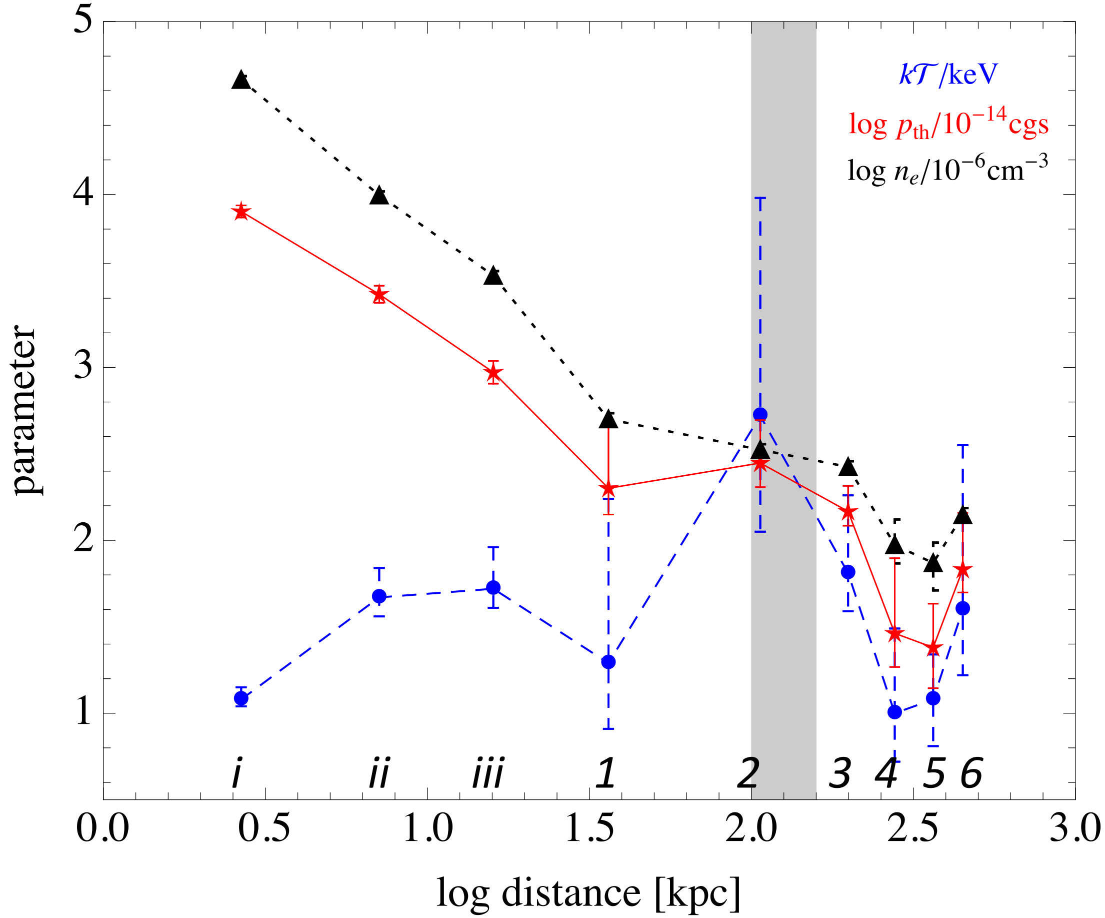
- BH mass M_{BH} = 3.9e9 $M_\odot$, one of the largest measured dynamically (McConnell +11), above the values implied by the M_{BH}-σ and M_{BH}-L_{bulge} scaling relations (1e9 $M_\odot$), and much above the "BH Fundamental Plane" (0.6e9 $M_\odot$)
- Line emission of the active nucleus of the LINER type, with $L_{H\alpha}$ = 1e40 erg/s; consistent with our new Chandra observations indicating $L_{X,nuc}$ = 2e41 erg/s
- The estimated accretion-related luminosity L_{nuc} = 2e43erg/s implies a very low accretion rate in the source, $\lambda = L_{nuc}/L_{edd} \approx$ 4e-5

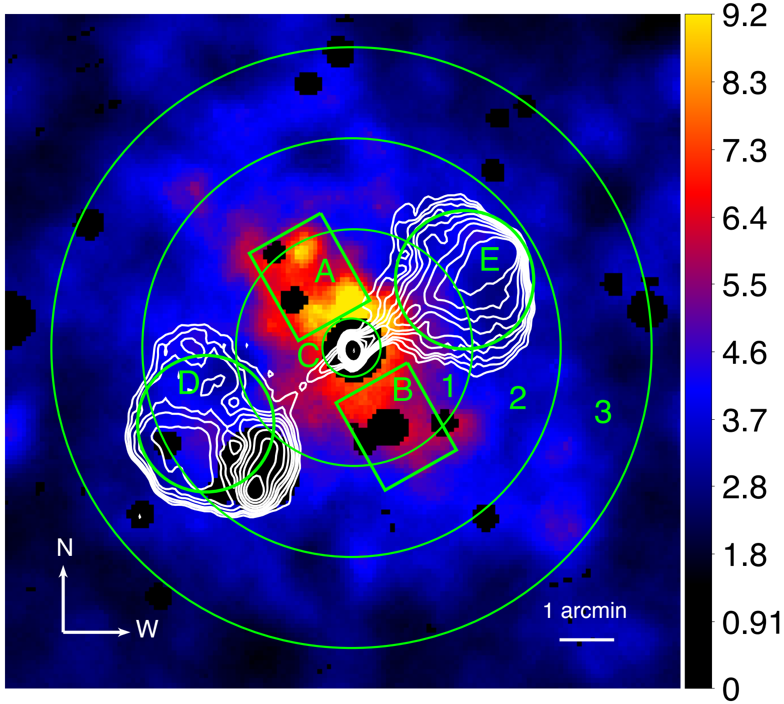
PKS B1358-113/A1836



- Outer cluster emission (32'' – 11'30'' annuli 1-6; XMM): ABS*APEC
- Inner cluster emission (2.5''-30'' annuli *i-iii* within region C; Chandra): ABS*APEC
- Lobes (regions E and D; XMM): ABS*PL
- X-ray filament (regions A and B; XMM): ABS*(PL+APEC)
- Core (<1.5'' within region C; Chandra): ABS*PL

PKS B1358-113/A1836





- Total cluster luminosity $L_{0.3\text{-}10keV}$ ≈ 4e42 erg/s and the average cluster temperature kT ≈ 1keV consistent with the L_X-T relation derived for clusters and groups of galaxies (poor cluster)
- Gas temperature and density enhancements around the edges of the PKS B1358-113 radio structure revealed by the de-projected cluster profiles (but no obvious emissivity enhancements)
- Accretion radius (r_A ~ 200pc) still unresolved (1'' = 0.71 kpc)

PKS B1358-113/A1836

- $\dot{M}_{acc} = \lambda (\eta_d/0.1)^{-1} \dot{M}_{Edd} \approx 2e\text{-}4\ \dot{M}_{Edd} \approx 0.02\ M_\odot/yr$ for the accretion disk radiative efficiency η_d at the level of a few percent (Sharma +07)
- Since we do not resolve the accretion radius in the system, we can estimate only a broad range of the Bondi accretion rate: $0.03\ M_\odot/yr << \dot{M}_B << 2.5\ M_\odot/yr$; this is much higher than the measured accretion rate $\dot{M}_{acc}$
- The fact that $\dot{M}_{acc} < \dot{M}_B$ is consistent with the expected mass-loss in radiatively inefficient accretion flows, $\dot{M}_{acc}(r<r_A) = (r/r_A)^\kappa \dot{M}_B$ with $0<\kappa<1$ (Kuo +14, Nemmen & Tchekhovskoy 14)

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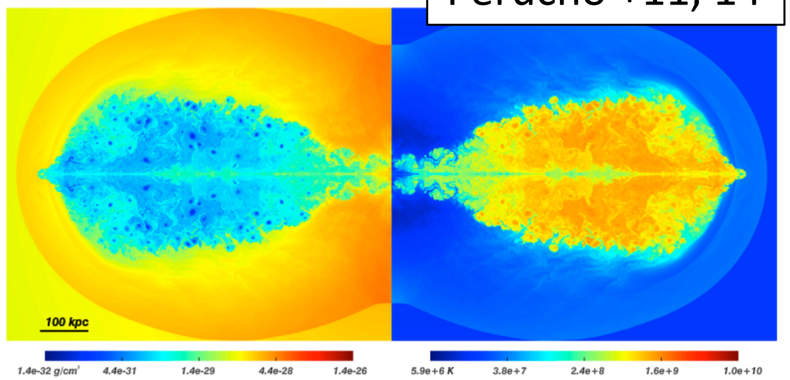
Also

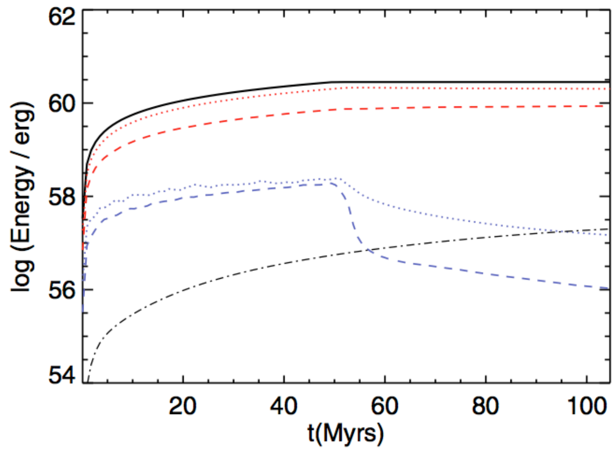
- Maximum jet kinetic luminosity $L_{max} = 3\, \dot{M}_{Edd}\, c^2 \approx 3e45$ erg/s (McKinney +12, Tchekhovskoy +14)
- L_j-L_{rad} scaling relations derived for cluster radio galaxies (Birzan +08, Cavagnolo +10, O'Sullivan +11) return $L_j \sim (1\text{-}3)e44$ erg/s; these relations are derived assuming sonic expansion of the lobes in the cluster atmosphere ($\tau_s \sim 300$ Myr); and indeed for the analyzed system $L_{cav} = 4\, p_{th}\, V_l / \tau_s \sim 1e44$ erg/s
- Spectral analysis of the radio lobes at radio and X-ray frequencies indicates the lobes are over-pressured with respect to the surrounding medium, $p_l > p_{th}$, and relatively young, $\tau_j < 80$ Myr $<< \tau_s$; therefore $L_j > 4\, p_l\, V_l / \tau_j > 5e44$ erg/s

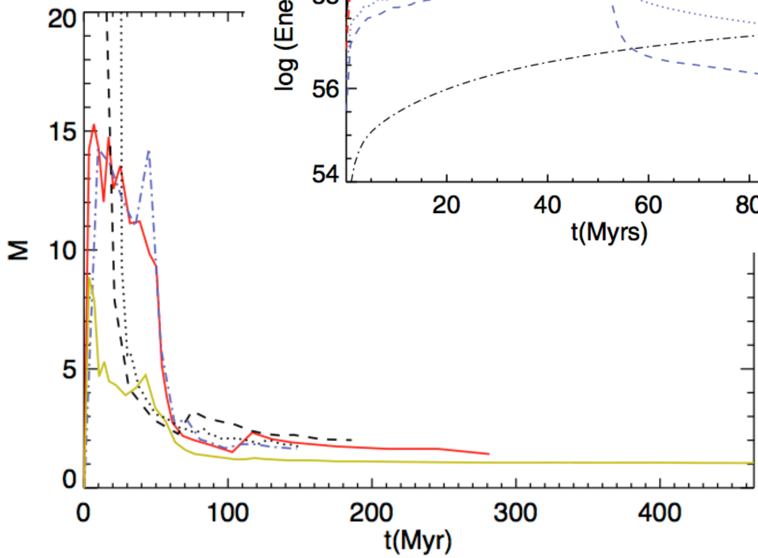
PKS B1358-113/A1836

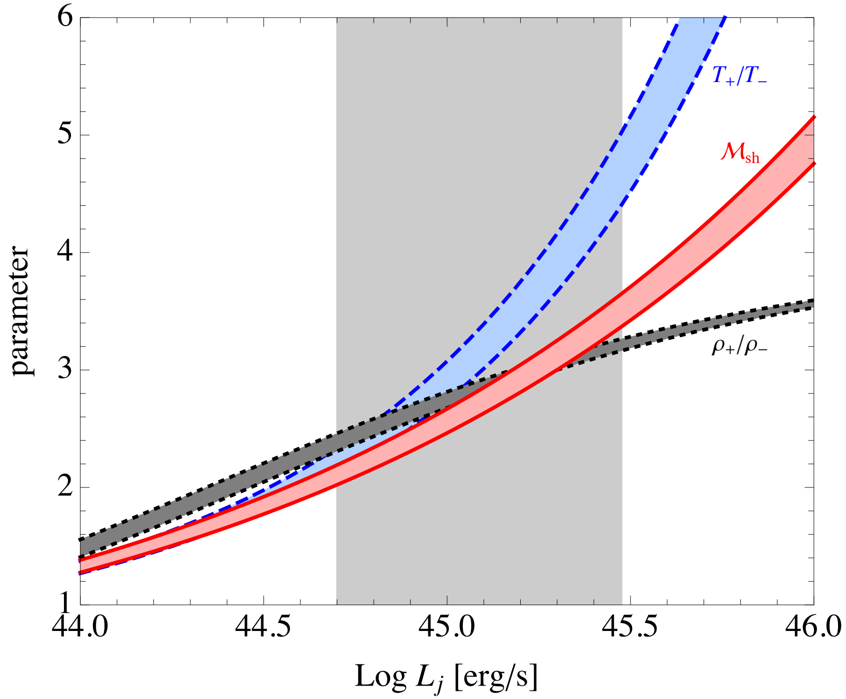
- In the analyzed system the jet production efficiency is close to the maximum expected level: $L_j \approx (0.5\text{-}3)\ \dot{M}_{acc}\ c^2 \approx (0.5\text{-}3)e45$ erg/s
- The standard evolutionary model of FRIIs applied to PKS B1358-113 confirms the supersonic expansion, with about half of the total jet energy, $E_{tot} = 2\ L_j\ \tau_j \sim (2\text{-}8)e60$ ergs, used for the shock-heating of the surrounding gas.
- The model-derived shock Mach number $M_{sh} \approx 2\text{-}4$ is consistent with the de-projected cluster profiles

Perucho +11, 14









Conclusions

- PKS B1358-113 is under-luminous in radio with respect to its FRII appearance
- BH mass much above the value implied by the BH fundamental plane
- Low accretion rate below the Bondi value, consistently with the expected mass-loss of RIAF
- Jet power higher than the cavity enthalpy divided by the sound-crossing timescale
- the L_j-L_{rad} or L_j-L_B scaling relations, often discussed for cluster radio galaxies, do not apply!
- Jet power close to maximum level allowed for a given accretion rate
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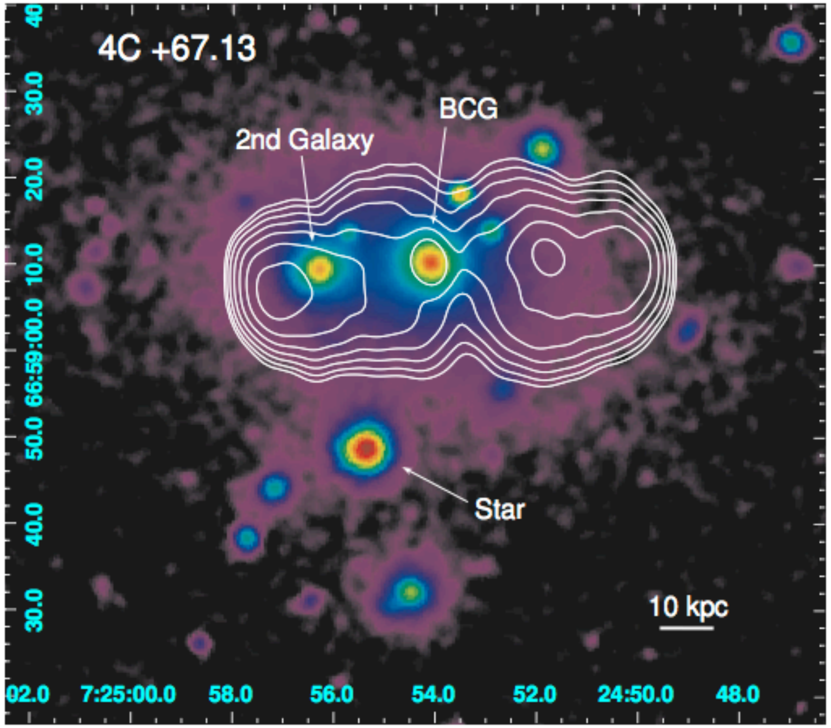
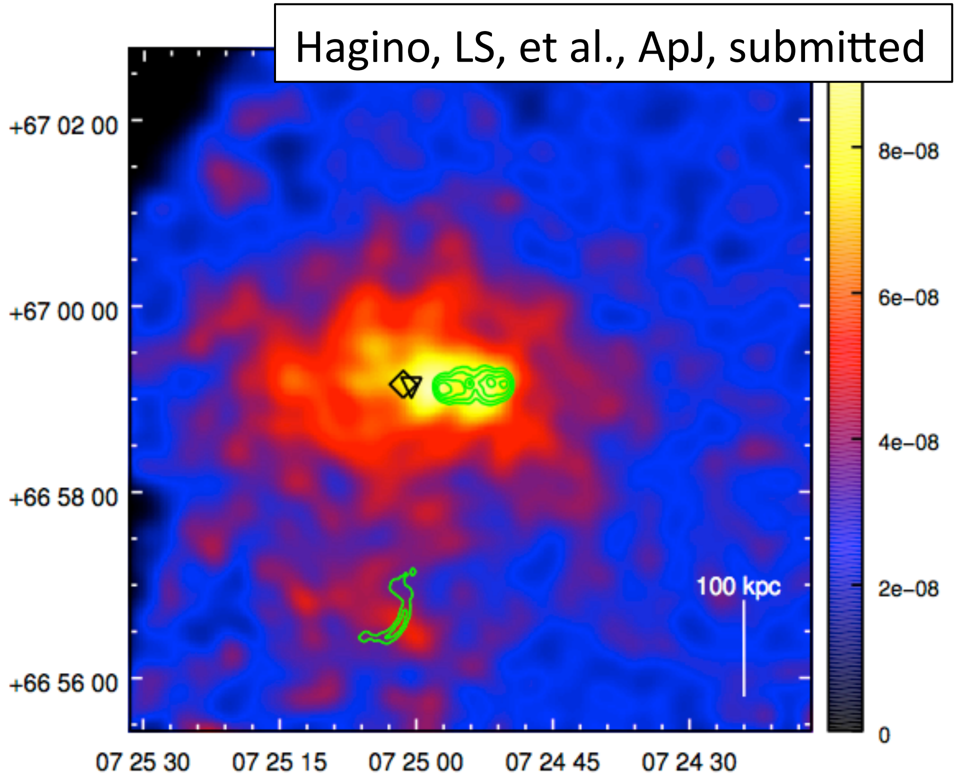
And in general

- Shocks surrounding radio lobes may be common and efficient in dissipating the jet kinetic energy (just difficult to be detected for various reasons)
- Need for detailed MWL studies of individual sources; to early to rely on various scaling relations derived for local weak sources (especially when discussing the radio-mode feedback in high-z Universe!)
- Jets seem to be produced with maximum allowed efficiency $L_j \sim L_{acc}$, depositing the bulk of the carried energy into their environments on 10s-100s of kpc scales

4C+67.13/A578

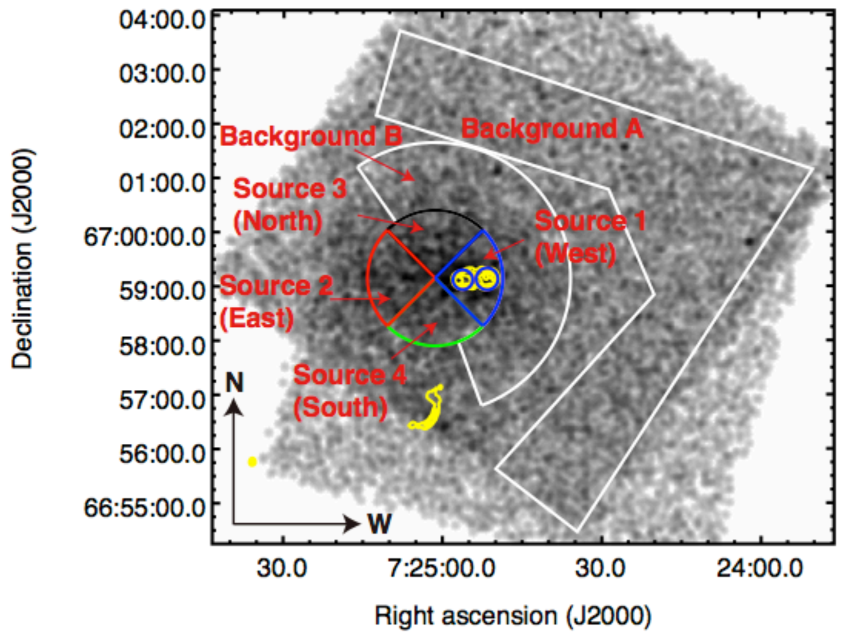


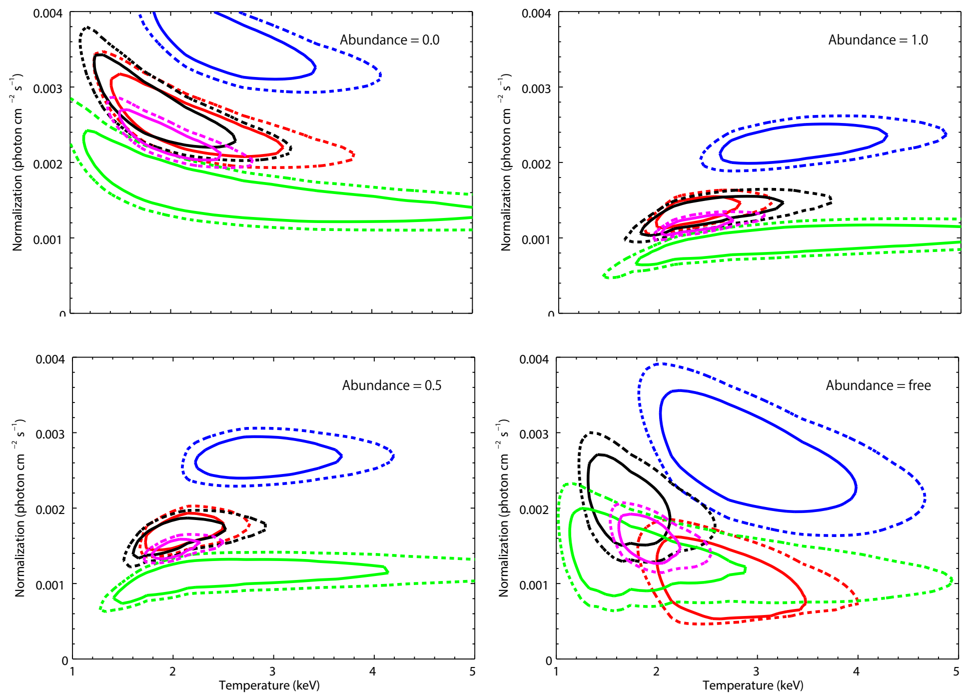


- Galaxy pair, both with LINER nuclei; merging cluster
- 4C+67.13 at rest with respect to its sub-cluster, displaced from the cluster emission peak (by 60 kpc)
- Luminosity $L_{0.5\text{-}7keV} \approx$ 2e43 erg/s and the average cluster temperature $kT \approx 2$ keV consistent with the L_X-T relation

4C+67.13/A578

Hagino, LS, et al., ApJ, submitted





- Nuclear and jet energetic very similar to PKS B1358-113!
- Large BCG/cluster emission peak offset supports the idea that BCGs are formed via galaxy mergers in one of the infalling groups prior to the cluster assembly
- the cluster galaxies and intracluster gas are falling onto the center of the cluster potential, evolving slowly toward a dynamical equilibrium, while the cluster atmosphere is heated gently by he radio jets/lobes produced with high efficiency in the low-accretion rate nucleus of the BCG.