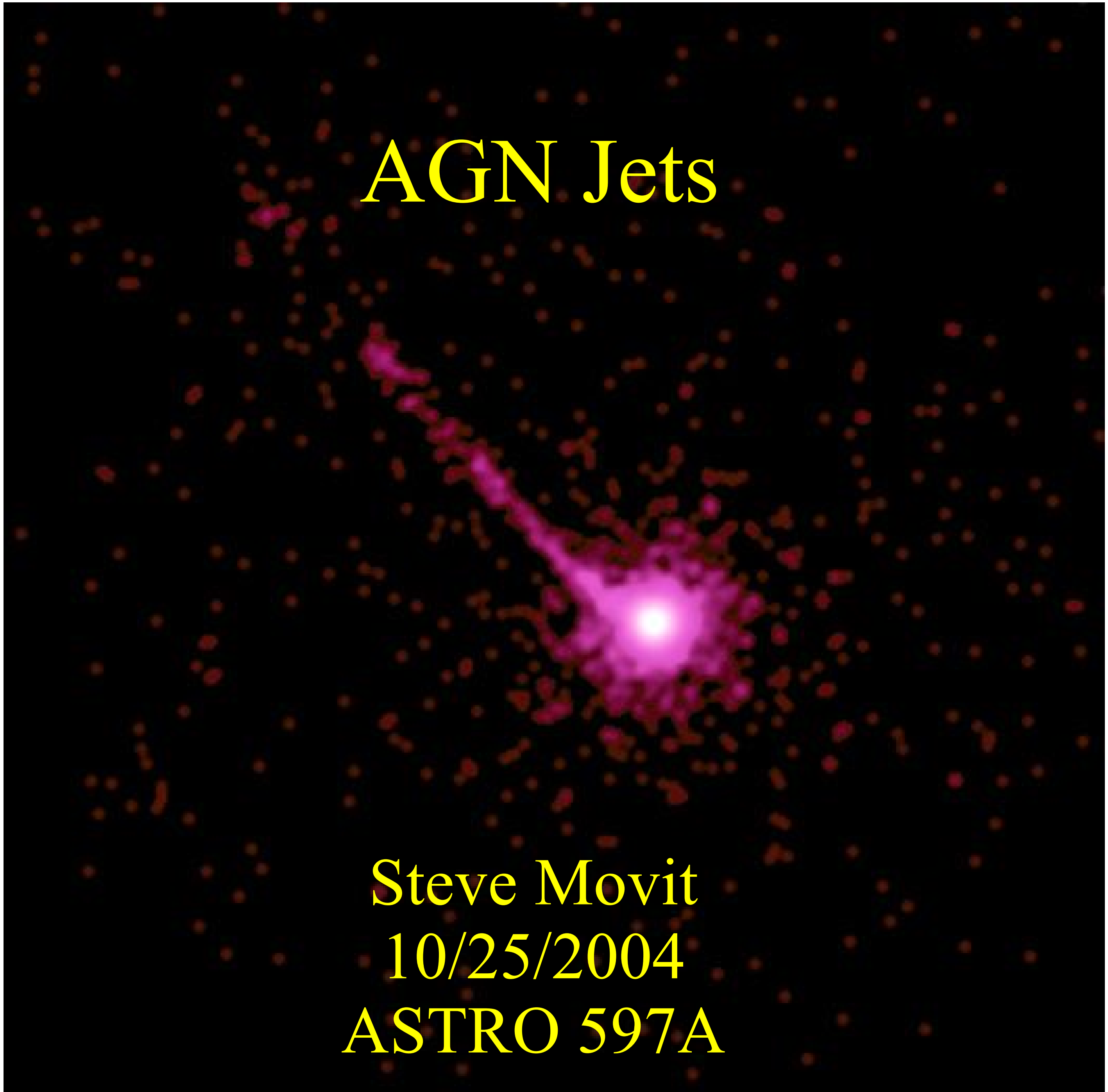


Credit: NASA/CXC/A.Siemiginowska(CfA)/J.Bechtold(U.Arizona)

Outline

- Before Chandra
- Physics of Jets · What we expect
  - Emission Processes
  - Types of Jets
  - Surrounding medium
- Detection · How we see them
- Results · What we see
- Future- what we'd like to see

Before Chandra

- Jets mainly studied in radio · Xray jets thought „exotic‰
- Einstein and ROSAT had few · M87, Cen A, NGC 6251
- Chandra first light · Xray jet PKS 0637-752
- Xrays found where no optical emision
- Synchrotron model breaks down from radio to Xray
- Now it seems that ALL radio jets have Xray counterparts

Synchrotron Review

- See Rybicki and Lightman Ch.6

$$Larmor\ Formula: P = \frac{(2q^2\dot{u}^2)}{(3c^3)} = \frac{(2q^2\vec{a}\cdot\vec{a})}{(3c^3)}$$

$$For\ relativity: \vec{a}\cdot\vec{a}\ is\ invariant$$

$$Beaming: a\|' = \gamma^3 a\|, a\perp' = \gamma^2 a\perp.$$

$$a\perp' = \omega_B v\perp.$$

$$\omega_B = \frac{(qB)}{(\gamma mc)}$$

$$P = \frac{(2q^2)}{(3c^3)}\gamma^4 \frac{(q^2 B^2)}{(\gamma mc^2)} v^2\perp.$$

More Synchrotron Review

$$Classical\ Electron\ radius: r_0 = \frac{q^2}{(mc^2)}$$

$$U_B = \frac{B^2}{(8\pi)} \qquad \sigma_T = 8\pi r_0/3$$

$$\tau_{rad} = \frac{E}{(-dE/dt)}$$

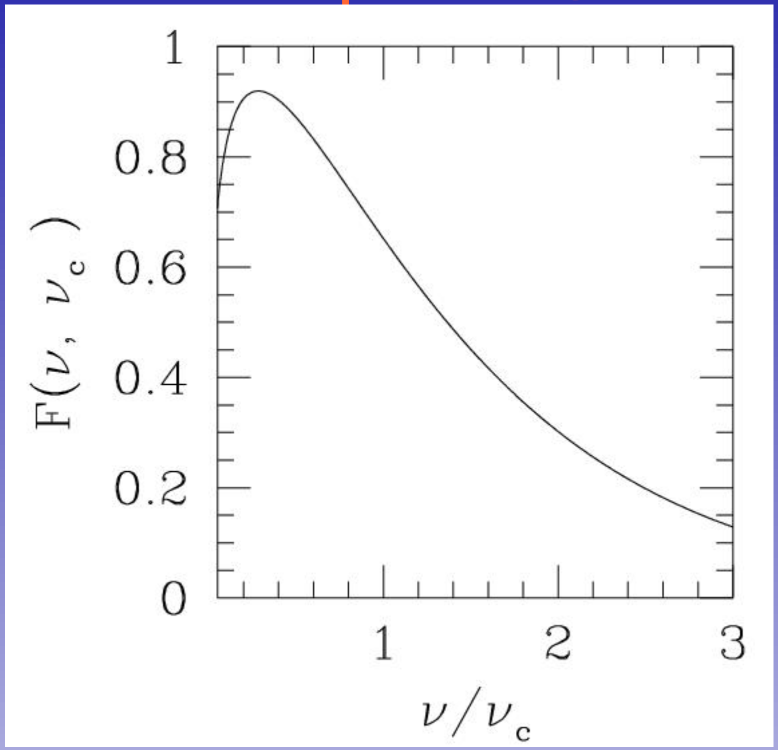
$$Voila: -dE/dt = 2\sigma_T c\gamma^2\beta^2 U_B \sin^2\alpha \quad (1)$$

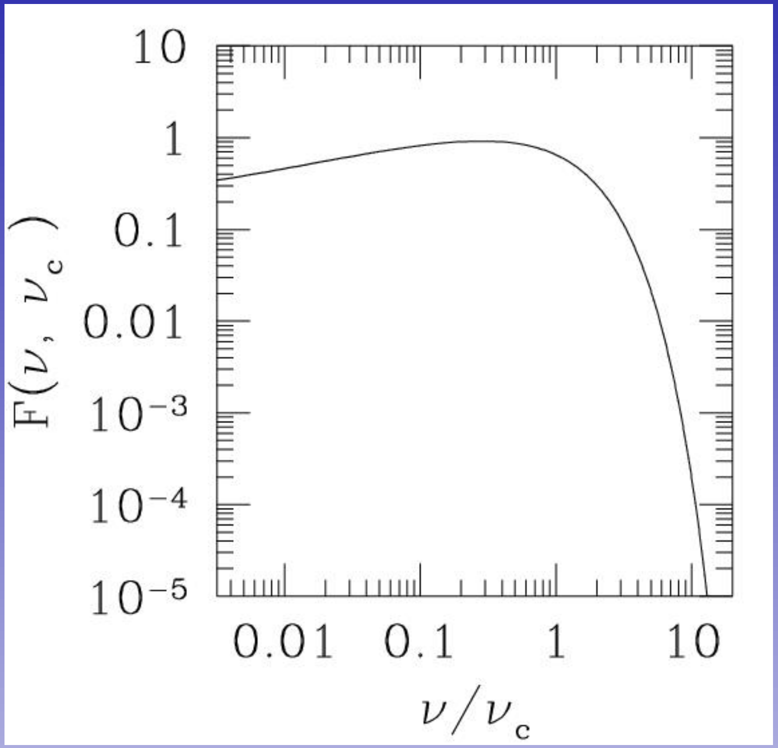
$$\nu_g = \gamma\omega_B/2\pi$$

$$Critical\ Freq.: \nu_c = (3/2)\gamma^2\nu_g \sin\alpha$$

Synchrotron · SDF and Luminosity

- Critical Freq is 30GHZ





From Worrall and Birkinshaw

$$X = \frac{\nu}{\nu_c}$$

$$F(\nu, \nu_c) = X \int_X^{\infty} (K_{(5/3)}(\xi) d\xi)$$

$$L_\nu \propto \int F(\nu, \nu_c) N(\gamma) d\gamma$$

Synchrotron · Power Laws and Luminosity

- The Big Punchline

$$L_\nu \propto \int F(\nu, \nu_c) N(\gamma) d\gamma, \; N(\gamma) d\gamma = \kappa \gamma^{(-p)} d\gamma$$

$$Requires: \gamma_{min}^2 \nu_g \ll \nu \ll \gamma_{max}^2 \nu_g$$

Analytical Result is a mess!!

- However, $L_\nu \propto \nu^{(-\alpha)}$
- Physics · Pret, mean probability per cycle that particle remains in jet and is shocked again

(Achterberg,et al 2001)

$$Ultarel.\, case: \alpha = 1 + \frac{(\ln 1/P_{ret})}{(\ln E_f/E_i)}$$

Fermi acceleration!

$$Nonrel.\, case: \alpha = \frac{(\rho_d/\rho_u + 2)}{(\rho_d/\rho_u - 1)}$$

Phew! Onto Inverse Compton

- Exact same energy rate loss formula! Provided:
- $\gamma h \nu_o \ll m_e c^2 - low\, energy\, photons!$
- Spectral distribution function differs:

$$X = \frac{\nu}{(4\gamma^2 \nu_o)}$$

$$F(\nu, \nu_o, \gamma) = X f(x), f(x) = X(1 + X - 2X^2 + 2X \ln X)$$

$$\bar{X} = \frac{(\int X f(X) dX)}{(\int f(X) dX)} = 1/3, \bar{\nu} = (4/3)\gamma^2 \nu_o$$

- When Compton scattering is on synchroton photons from jet, is synchrotron self-compton

Thermal Bremsstrahlung Emission

$$Stated: \frac{dW}{(d\omega\, dV\, dt)} = \frac{(16\pi e^6)}{(3\sqrt{3}c^3 m^2 v)} n_e n_i Z^2 g_{ff}(v, w)$$

$$Maxwell\ Velocity\ Dist'n (Isotropic): dP \propto v^2 \exp\left(\frac{(-mv^2)}{(2kT)}\right) dv$$

$$For\ a\ photon\ of\ freq.\ \nu,\ h\nu \leqslant \frac{1}{2} mv^2$$

- Average dW(v, ω)/(dω dV dt) over the velocity distribution
- $$\varepsilon_\nu = 32\frac{\pi}{3}\left(2\frac{\pi}{3}\right)^{.5} Z_i^2 g_{ff} n_i n_e m_e c^2 r_o^3 \left(\frac{(m_e c^2)}{(kT)}\right)^{.5} e^{\left(\frac{(-h\nu)}{(kT)}\right)}$$
-
- Integrate over freq., convert to P

$$\tau_{cool} = 2.5\frac{(kT)}{(\varepsilon \mu m_H)}$$

FR classification

- Paper: Fanaroff and Riley, 1974 MNRAS · Cambridge One Mile telescope
- "There is a definite relationship between relative positions of the high and low brightness regions of radio sources and their luminosity"
- Classified by ratio: distance between highest central bright. regions on either side of nucleus and total extent · relative position of hotspots
- > .5 Class II, < .5 Class I, High L Class II, Low L Class I
- Class I more complex structure

FR I

- FR I galaxy 3C 31 · note that jets starts right near core

FR I physics

- Low power, and a well defined beam head · this means good contact with external medium
- Based on 3C 31, jet has 3 regions: narrow jet w/ relativistic flow, flaring region bright in radio, outer region with steady deceleration
- Outer region is where deflection takes place
- Knots are a mystery
- Acceleration takes place in knots

FR II

- FR II galaxy 3C 220.1 · clear separation of lobes from core · high power

FR II Physics

- FR II is supersonic w.r.t ISM- bow shock forms at end of jet · we see „well collimated jets feeding edge brightened lobes‰
- $$c_s = \sqrt{\left(\frac{(\gamma k T)}{(\mu m_H)}\right)}$$
-
- $$M = \frac{v_{adv}}{c_s}$$ Assume strong shock (Rankine-Hugoniot)
- Get simple relations

$$\frac{P_2}{P_1} = (5M^2 - 1)/4, \frac{\rho_2}{\rho_1} = \frac{(4M^2)}{(M^2+3)}$$

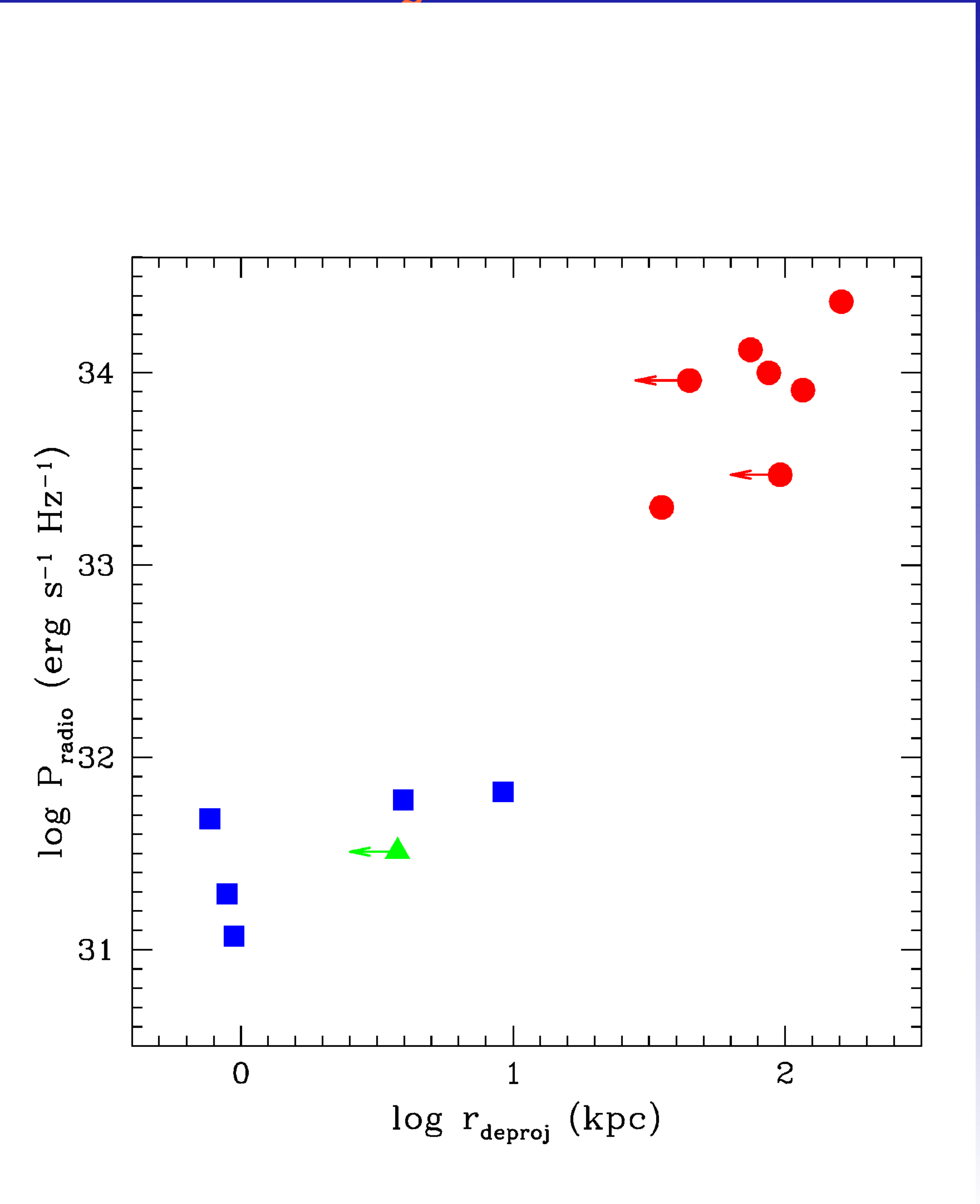
$$\frac{T_2}{T_1} = (5M^2 - 1)\frac{(M^2+3)}{(16M^2)}$$

FR I/ II Physics

- Difference (according to Sambruna) lies in jet pressure · fits with idea of luminosity discrimination
- Jet pressure in FRII becomes comparable to ambient farther out · this is where shocks form
- Would expect innemost knot closer to core in FR I than in FRII · explore?
- In FRI knots fit radio-optical synchrotron spectrum
- FRI Xray morph. Fairly uniform

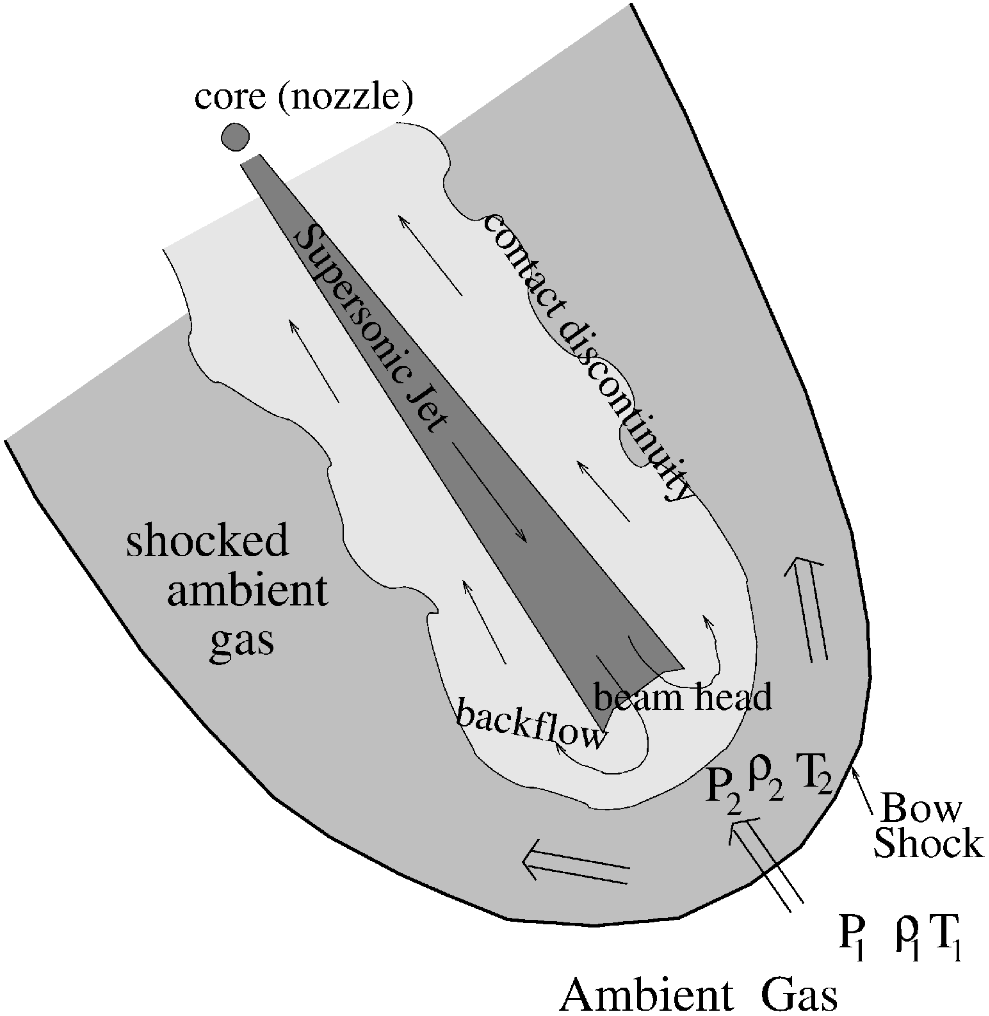
FR I/ II Physics

From Sambruna, et al.



Jet Schematic

From Worrall and Birkinshaw



- Jet terminates at hotspot - light gray is radio emitting fluid · heats ambient gas producing X-rays

Jet Structures

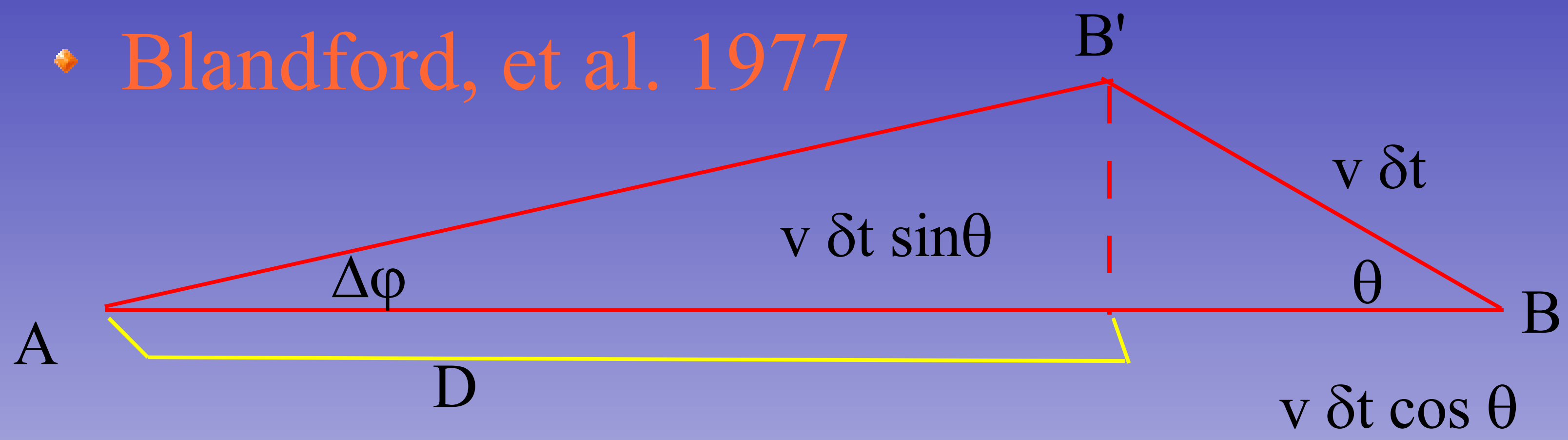
- Jet features defined based on radio
- Jet · narrow feature, 4x as long as it is wide
- Lobe · radio emission not in jet
- Hotspot · compact feature in lobe
- Knot · compact feature in jet
- End of jet: end of emission, 90 degree change of direction, decollimation by 2x
- Knots are most likely to have X-ray counterparts

Magnetic Fields

- Field orient. determined by linear polarization in radio
- $$\pi_L = \frac{(\alpha+1)}{(\alpha+5/3)}$$
- Significant pol. indicates lack of thermal material · otherwise differential between front and back of jet would depolarize it
- Circular polarization (mentioned later) also seen in pc scale jets
- Is this e+ e-?

Superluminal Motion

- VLBI obs. of AGN show jets w/ multiple comp. around bright cores
- These comp. Expanding · separating w/ Vt ~ 10c
- Blandford, et al. 1977



Adapted from Peterson (1997)

$$\beta_T = \frac{v_T}{c} = \frac{D}{c}\frac{(\Delta\phi)}{(\Delta t)} = \frac{(v\sin\theta)}{(c(1-\beta\cos\theta))} = \frac{(\beta\sin\theta)}{(1-\beta\cos\theta)}$$

$$Maximize\ \beta,\ get\ \beta_T^{max} = \beta\gamma,\ \gamma\ can\ be\ arb.\ large$$

Bulk Relativistic Motion · Effects

- Relativistic Doppler Factor:
- $$\delta = \frac{1}{(\Gamma(1-\beta\cos\theta))}$$
- $$L_{nu}\, increases\, by\, \delta^{(2+\alpha)}$$ $$R_J = \left(\frac{(1-\beta\cos\theta)}{(1+\beta\cos\theta)}\right)^{-(\alpha+2)}$$
- Boosting by factor of alpha due to blueshift
- Core dominance:

$$R_{cd} = \frac{R_{(cd,(\cos\theta=0))}}{2}\left((1-\beta\cos\theta)^{-(\alpha+2)} + (1+\beta\cos\theta)^{-(\alpha-2)}\right)$$

External Medium

- Jets mostly distinct from nucleus · X-rays arise from interaction of hot jet gas with cool dense medium
- Jet is in hydrostatic equilibrium · like stellar interior $\nabla P = -\rho \nabla \phi$
- Ideal Gas: $P = \frac{(n_p k T)}{(X \mu)}, solar\, abund.\, \mu = .6$
- Spherical sym.: $\frac{(d\Phi)}{(dr)} = \frac{(G M_{tot}(r))}{r^2}$

More External Medium

- Follows "Isothermal Beta Model" - see Cavaliere and Fusco-Fermiano, 1978
- $\rho = \rho_0 \left(1 + \frac{r^2}{r_c^2}\right)^{(-1.5\beta)}$ $\beta = 2/3 \frac{(\mu m_h)}{(kT)} \frac{(GM_c)}{r_c}$
-
- Beta depends on ratio of grav. pot. to thermal E per unit mass
- NFW say its unphysical · measured beta's don't match theory · NFW ain't perfect either
- Bottom line · density has power-law structure with dimensionless parameter representing balance of gravity and thermal motions

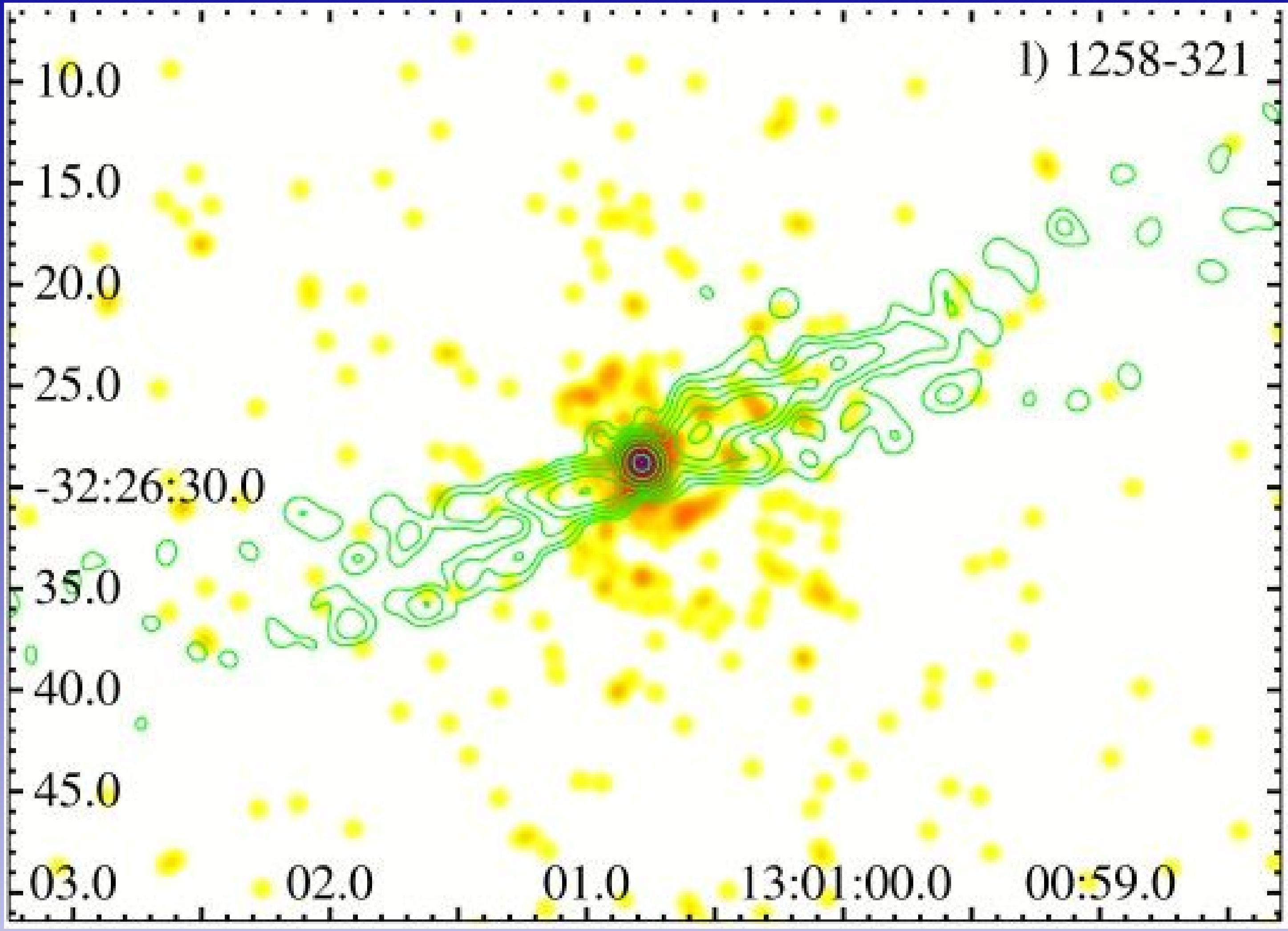
More External Medium -Surface Brightness and Ion Ratio

- Density and T of medium can be determined from surface brightness, but it's a mess
- XSPEC uses the magic normalization mentioned in class
- $$N=\frac{(\int n_e n_p dV)}{(4\pi D_A^2(1+z)^2)}=\frac{((1+z)S_\nu)}{\Lambda_\nu}$$
- Da is angular diameter distance and (1+z) is for expanding universe, Lambda is emissivity
- S and Lambda are fit, Ne and Np are "pulled out" using isothermal beta, and

$$\frac{n_e}{n_p}=\frac{(1+X)}{(2X)}=1.8\ for\ solar$$

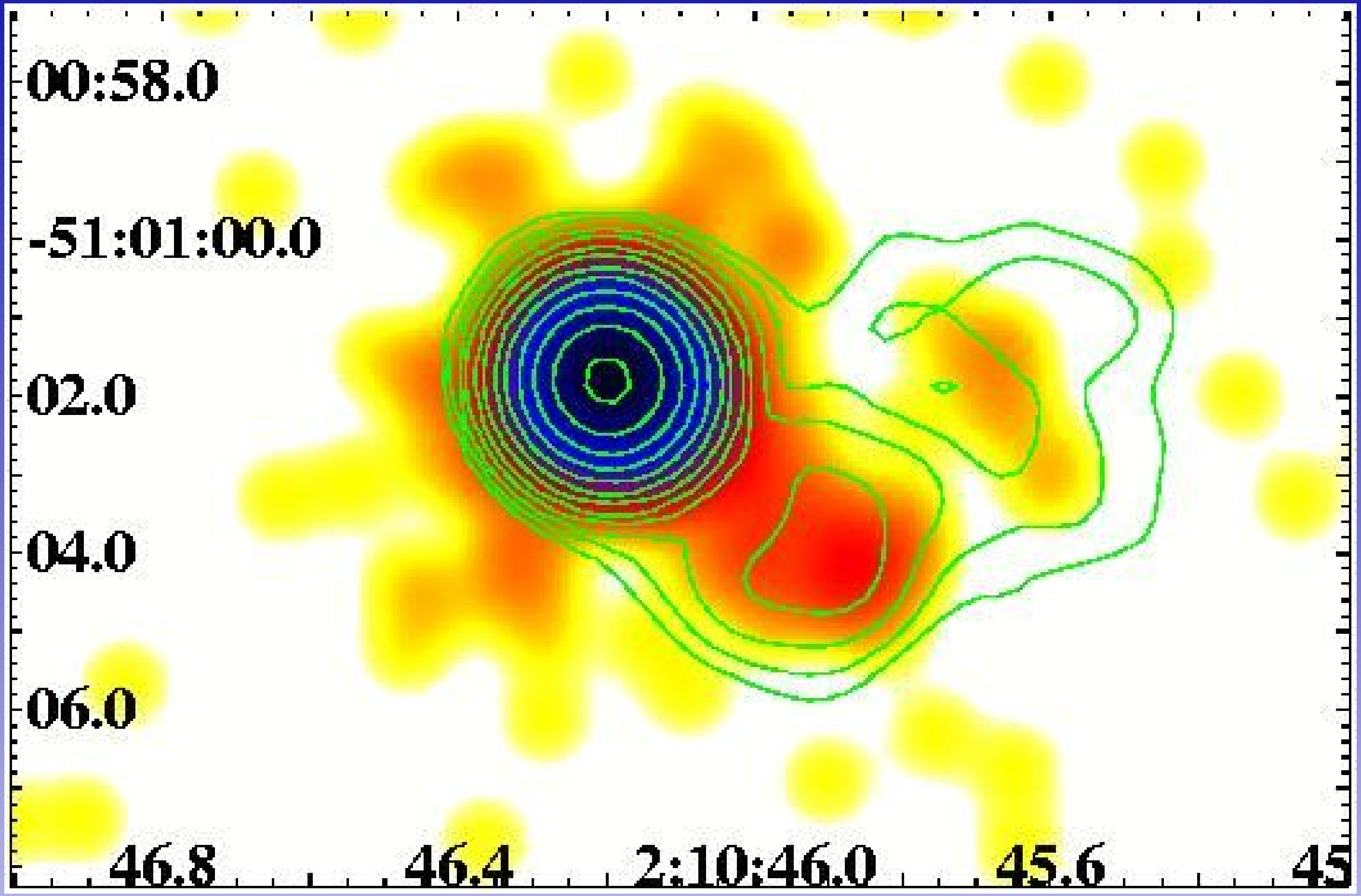
PKS 1258-321

Marshall et al.



- Core dominated, FRI, no X-ray emission from the jets
- Extended X-ray halo?

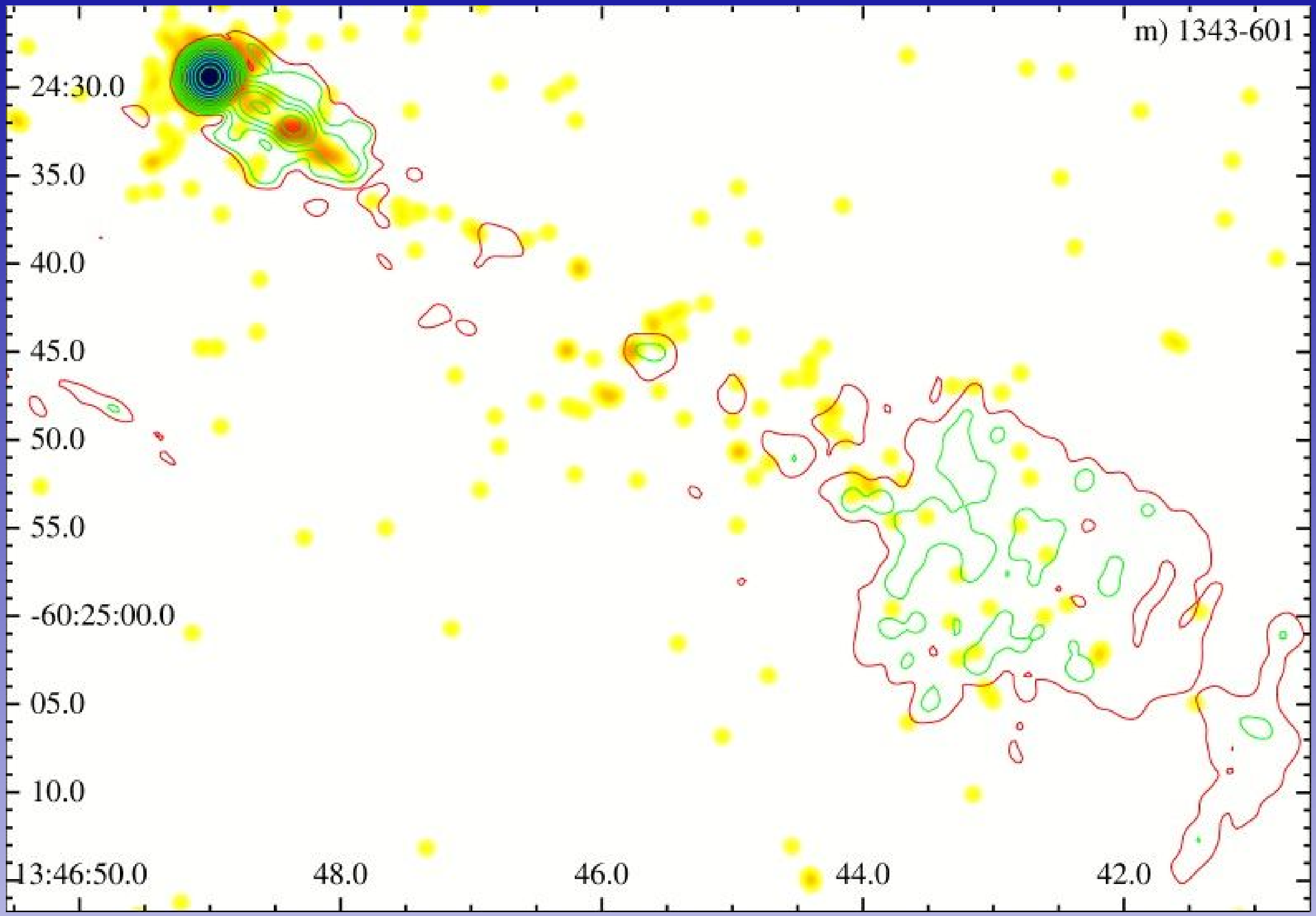
PKS 0208-512



Marshall et al.

- 4‰ long jet in X-ray, coincident with radio · X-ray cuts out at 90 degree bend · radio polarization is at 90 degrees to jet direction

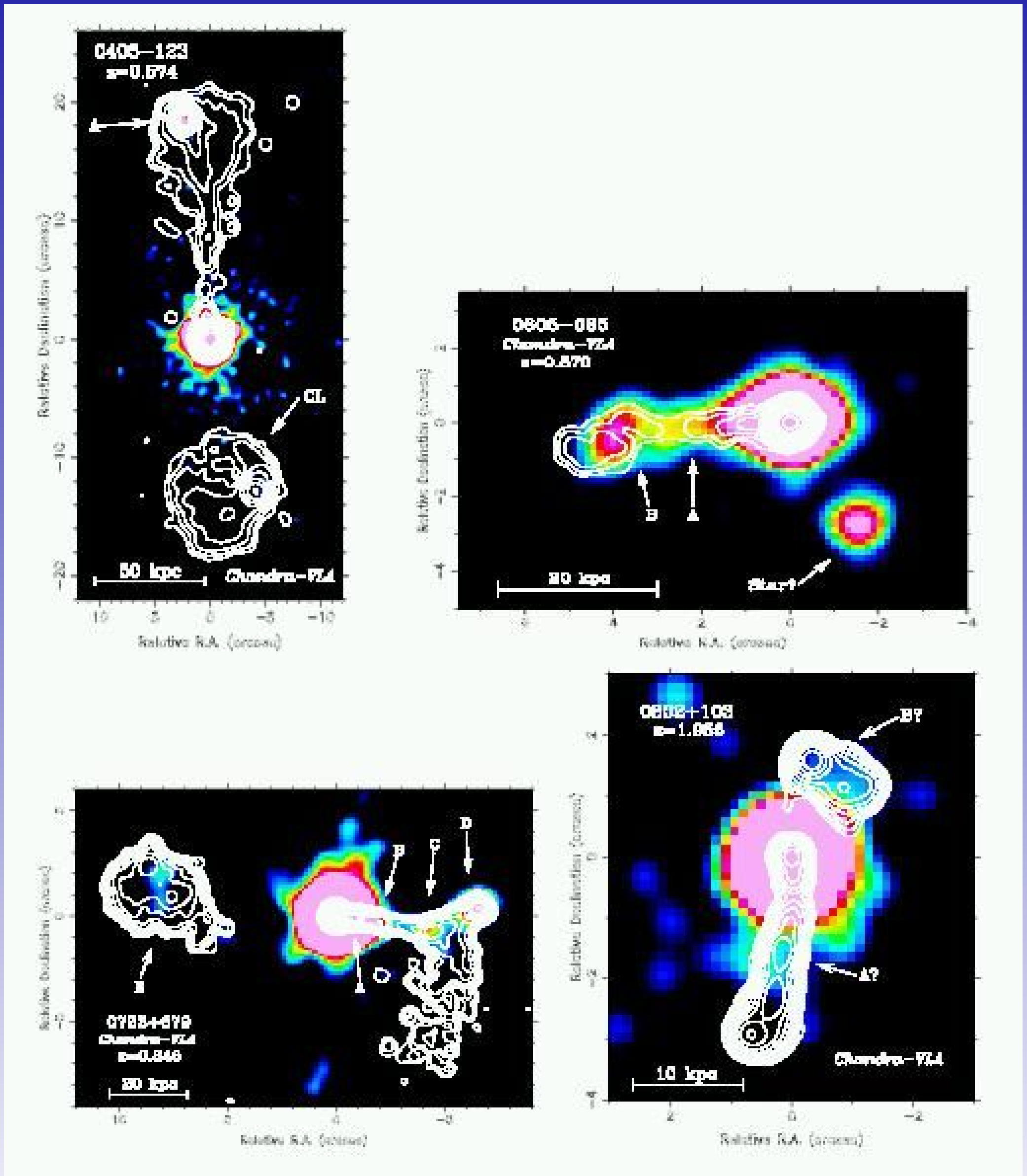
PKS 1343-601 / CEN-B



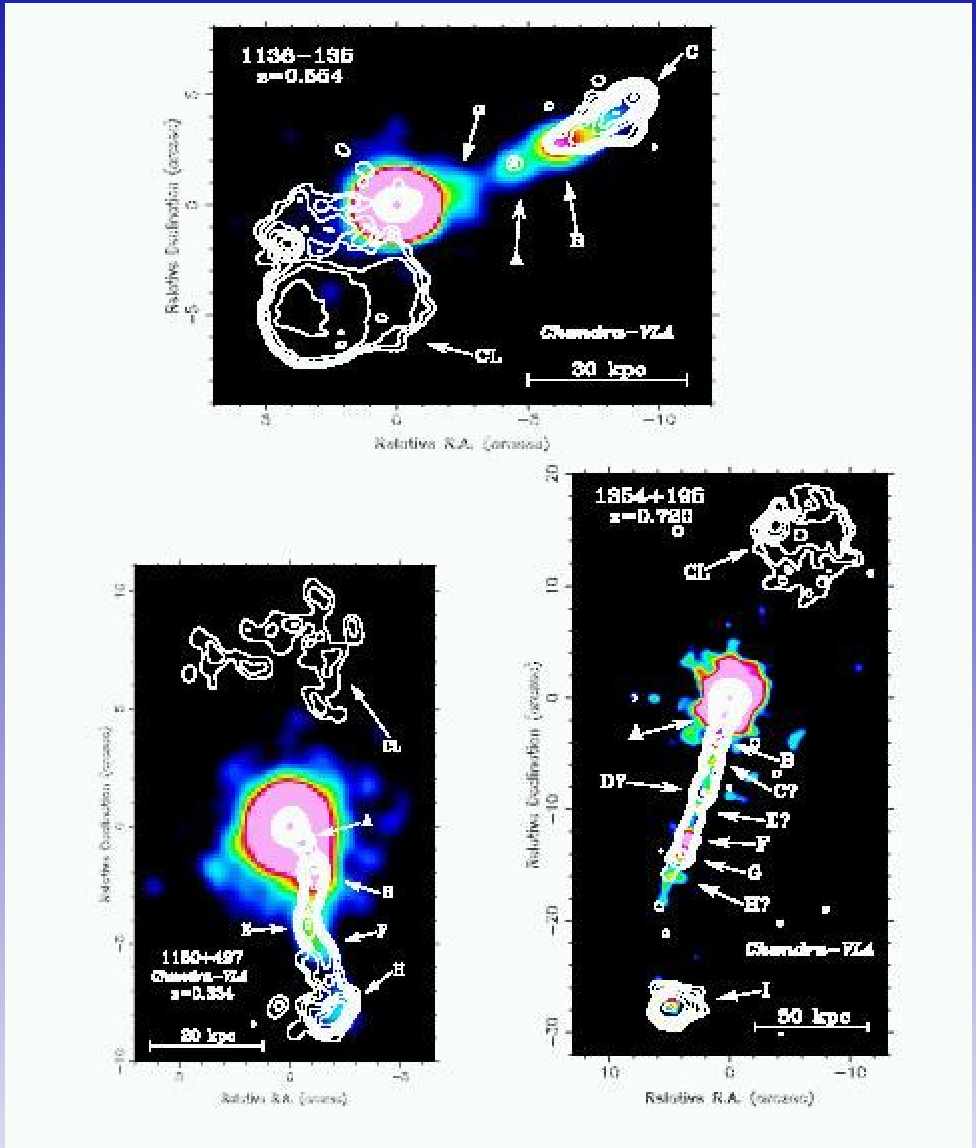
Marshall et al.

- Very one sided, knot detected in X-ray, some yellow blobs significant, upstream and in lobe

Sambruna et al.



Sambruna et al.



What can we learn?

- Sambruna et al find ~ 59% detection in X-ray of radio features, around same in optical
- Seems that most all FR I's have X-ray counterparts
- All sources in Sambruna sample are one-sided - beaming
- Composition: e- & e+ pairs expected near AGN · Circular polarization from mode conversion detected
- Evidence for p+ & e- plasma exists too · p+ outnumber e- in CR by 100x
- Also, interaction w/ medium should enhance p+ content
- However, data point to a low mass jet, insuffcient pressure for a p+ & e- jet

Spectral Modeling

- SED modeled for aperature of 1-1.5", limited by Xray
- SED power law from radio through optical to Xray determines emission mechanism (IC, synch., thermal)
- If optical lies on power law between radio and Xray, then 1 method works for all
- If below, then synch. provides low freq. and IC provides high
- Synchtron dominates when: $\alpha_{ro} < \alpha_{ox}$
- For most jets, Xray is a separate process
- Alpha rx increases from inside of jet out
- Confirms theory of W&B

More Spectral Modeling

- A single e- population can produce both synch. and IC present · need input photons from CMB
- Any seed photons will do · CMB is most likely
- Energy density of CMB scales (1+z)^4
- For knots inside host, starlight works too
- As shown earlier, relative lifetimes for the emission processes vary, synch. short @ short WL
- Restricts synch. to more compact reg.
- IC/CMB model · huge cooling times
- Need consistent Xrays along jet - PKS 1954+196 shown before

More Spectral Modeling

- Sambruna finds trends based on large sample:
- "Common conditions along jet determine the observed properties of emission features"
- Possible reason for FR I/II: location where jet and ambient P equalize · causes major slowdown
- Discrim. Param · Jet P (power), more luminous sources slow down later
- "Xray emission from extended radio jets with α_{rx} *around* .8 is common in AGN"
- Knots have different phys. process

More Spectral Modeling

- Marshall has similar findings on IC/CMB, interesting results on PA
- First, need to define min. B field strength · find energy in e- by integrating power law (at min. Ue = 4/3 Ub):
- $U_e = \kappa m_e c^2 \int_{(\gamma_{min})}^{(\gamma_{max})} \gamma \gamma^{(-p)} d\gamma = \kappa m_e c^2 \int (\gamma_{min})^{(\gamma_{max})} \gamma^{(-2\alpha)} d\gamma$
- $Know\ L_\nu \propto \kappa \nu^{-\alpha} B^{(\alpha+1)}$
- Integrate and plug in for kappa, define K as baryon ratio, eta=f=filling factor
- $$U_{part.} = C_1 B^{-(\alpha+1)} \frac{(1+K)}{(\eta V)} L_{nu} f(\alpha)$$
- Marshall: alpha=.8, gamma=1

More Spectral Modeling

- From there, derived quantities and some assumptions lead to:
- $\Gamma\,\delta(1+u_j{}')=\frac{(1-\beta+\mu-\mu\beta)}{(1-\mu\beta)^2},\ \mu_j = cosine\ of\ l-o-s\ angle$
-
- $Assume\ \Gamma=10, know\ \delta=[\Gamma(1-\mu\beta)]^{-1}$
- Can solve for PA!
- Jet angles around 20 to 30 degrees

What We Don't know:

- Lots! Biased samples · current surveys have selections effects: L, z
- Need obs. of Xray ISM
- Deep observations · would like to see continuous emission along all jets
- Limited to 1‰ aperature · could be overestimating sizes
-

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