The Origin of X-ray Emission from Large-scale Quasar Jets

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Key Issue: Jet Formation
Blandford-Znajek Mechanism

GRMHD simulations by J. McKinney

Strong polar B-field (accretion disk) around a spinning BH

Rotational energy of black hole → Relativistic Jet

x-z plane

x-y (disk) plane
Global radiation-MHD simulations (Ohsuga+ 09, 11)

Ubiquitous outflow from any modes of accretion flow!

Thick disk + rad-driven jet/outflow
Thin disk + weak outflow
Thick disk + mag-driven jet/outflow
Key Issue: AGN Feedback
Bubble created by jet

NGC1275: SMBH w/ jet
Jet-driven Turbulence in Cluster

1. Measurement of Cluster Mass (sensitive to cosmological parameters)

- Hydrostatic mass equation becomes

\[ M(r) = -\frac{r^2}{G\rho_{ICM}} \frac{d(P_{\text{therm}} + P_{\text{turb}})}{dr} \]

- Neglecting \( P_{\text{turb}} \) \( \rightarrow \) Mass is underestimated

2. Cosmic-ray Acceleration

Kolmogorov

\[ E(k) \propto k^{-5/3} \]

SMBH \( \rightarrow \) Jet \( \rightarrow \) Turbulence

Abell 3667
ASTRO-H is an international X-ray observatory, which is the 6th in the series of the X-ray observatories from Japan. More than 160 scientists from Japan/US/Europe/Canada.

**ASTRO-H Mission**

- Launch site: Tanegashima Space Center, Japan
- Launch vehicle: JAXA H-IIA rocket
- Orbit Altitude: 550km
- Orbit Type: Approximate circular orbit
- Orbit Inclination: ~31 degrees
- Orbit Period: 96 minutes
- Launch: 2015

**US Participation**

- NASA (US PI: Rich Kelley)
  - Micro Calorimeter Array/ADR
  - Two soft X-ray Telescopes
  - Eight Science Advisors
  - Pipeline Analysis

Science operations will be similar to those of Suzaku, with pointed observation of each target until the integrated observing time is accumulated, and then slewing to the next target.
The Perseus Cluster

ASTRO-H Observation:
Turbulence and Bulk Motions in Clusters of Galaxies

Fe Kα line (He-like)
Quasar Large-scale Jets

Jet properties such as:
- Power
- Lorentz factor
- Composition ($e^-e^+$)
- B-field

![Image of 3C 273 jet with VLA, Spitzer, Hubble, and Chandra labels and high-energy emission on the left, low-energy emission on the right.](image)
Two classes: low/high power jets

$L_X/10^{40}\text{erg s}^{-1}$

X-ray = Synchrotron

X-ray = ???

Cen A (D=3.5 Mpc)

3C 273 (z=0.156)

Harris & Krawczynski (2006)
Origin of Chandra quasar jets?

Chandra 1st light:
PKS 0637-752

(Chwartz et al. 2000)

“Beamed IC/CMB” model

"Proton Synchrotron Radiation"

\[ \nu_c \sim 2 \times 10^{18} \, B_{\text{mG}} \, E_{18}^2 \, \text{[Hz]} \]

\[ L_X \sim 0.1 \, \frac{W_p}{t_{\text{syn}}} \sim 0.4 \times 10^{42} \, B_{\text{mG}}^4 \, \text{erg s}^{-1} \]

\[ E_p \sim 10^{18} \, \text{eV} , \quad B \sim \text{mG} \]

Syn

X-ray

E/p Synchrotron models

(a) 2nd electron synchrotron

e.g., turbulent acceleration

Stawarz&Ostrowski 02

(b) proton synchrotron

Aharonian 02
Chandra surveys


Sambruna+ (2004)

X-ray detection rate is high: about 50%
Small- and Large-scale Jets

Marshall+ 2001

Chandra X-ray

“Blazar Core”
✦ Synchrotron + IC
✦ Beaming $\delta \sim 10$-20

Chernyakova+ 2007
Tueller+ 1999, 2006
Kataoka+ 2003

“Extended Jet”
✦ Synchrotron + [IC or Syn]
✦ If IC, strong beaming $\delta \sim 20$
super-Eddington jet (e/p)

Jester+ 2006, 2007
Uchiyama+ 2006

Uchiyama (2008)

3C 273 and its Jet

Chandra X-ray
Double Synchrotron Model

Uchiyama+ 2006
(see also Jester+ 2006)

Image: 3C 273 jet, VLA, Spitzer*, Hubble, Chandra (* deconvolved)

- knot size: ~ 0.3” ~ 1 kpc
- B ~ 0.1 mG (eq)

Graphs:
- Optical (polarization) = X-ray
- LE and HE:
  - Different slopes
  - $\alpha_1 \approx 0.7$
  - $\alpha_2 \approx 1.0$
HST Far-UV observation confirms the optical-X-ray connection.
Recent Fermi measurement rules out IC/CMB

Meyer & Georganopoulos (2014)

Data from Uchiyama+ 2006

**Figure 2.** SED of knot A (data from Uchiyama et al. 2006 and Jester et al. 2005, 2006), along with the Fermi 95%, 99%, and 99.9% upper limits described in Section 2 and Table 1. The numerical SED calculated at equipartition (solid line) overproduces the 3–10 GeV 99.9% Fermi upper limit, ruling out the IC/CMB model for the X-ray emission of knot A. The broken line is the highest level the IC/CMB component can have without violating the 95% 3–10 GeV band Fermi upper limit.
Quasar PKS 0637-752: The First Chandra Jet

Mehta+ 2009

Hubble NICMOS+ACS data indicate spectral hardening in the optical band:

\[ \alpha_{\text{NICMOS-WFPC2}} = 0.91 \pm 0.06 \]
\[ \alpha_{\text{WFPC2-ACS}} = 0.35 \pm 0.12 \]

The onset of the HE component can be seen in “blue” light.
PKS 1136-135 (z=0.55)

Uchiyama+ (2007)

Spitzer  Chandra

Quasar: PKS 1136-135

SEDs similar to 3C 273

Viewing angle would not be very small
--- Beamed IC/CMB model unfavorable
PKS 1136-135: HST Polarimetry

Cara, Perlman, Uchiyama+(2013)

B-field direction from radio polarimetry

B-field direction from HST polarimetry

$\Pi = 37\pm6\%$

$\Pi \approx 8\%$

$\Pi = 11\pm2\%$

$\Pi \approx 70\%$

$\Pi = 37\pm6\%$

Chandra image w/ radio (8.5 GHz)

HST (F555W)
Highly polarized optical emission is detected. The degree of polarization is larger than that predicted for beamed IC/CMB. Beamed IC/CMB model becomes unfavorable, confirming synchrotron origin of X-rays.
Summary

We discussed the origin of the X-ray emission from the large-scale quasar jets:

Recent studies indicate the high-energy component (optical-X-ray) is of synchrotron origin:

- Spectral shapes and energetics (3C273)
- Fermi upper limit (3C273)
- Optical polarization (PKS 1136-135)
- Counter-jet detection (3C353) Kataoka+ 2008

Electrons of 10-100 TeV can be accelerated in kpc knots despite severe synchrotron cooling