• The radio halo (40 kpc) of M87 (Virgo A) was one of the first radio sources detected (Bolton & Stanley, 1948).
• The Virgo cooling flow was the first extragalactic X-ray source detected (Byram et al., 1966).
• $3.2 \times 10^9$ Mo SMBH, 16 Mpc.
• One-sided jet (Owen, 1989) powering radio lobes interacting with X-ray thermal gas.
• Low emissivity cooling flow (some Mo/yr), heated by SMBH activity.
• Buoyant bubbles lift 1–10 Mo/yr from the core to the radio halo (Churazov et al., 2001).
The deepest extragalactic field observed by INTEGRAL

1660 pointings
20-60 keV, to optimize sensitivity
3.9 Ms elapsed time
Maximum effective exposure: ~ 775 ks

ISGRI allows exposure >100 Msec
i.e. sensitivity < 0.01 mCrab (10^{-13} cgs)
not limited by systematics.
34 sources:
5 Seyfert 1
4 Seyfert 1.5/1.8
8 Seyfert 2
4 blazars

LED 37894 (S2)
NH=6.7E22

MCG-03-34-064 (S2)
NH=9E23

\[
\frac{d\Phi(L)}{d \log L} = \frac{\Phi^*}{(L/L^*)^{-\alpha} + (L/L^*)^{-\beta}}
\]

\[
\log L^* = 43.66^{+0.28}_{-0.60} \text{ erg s}^{-1}
\]

\[
\alpha = 0.85^{+0.26}_{-0.38}
\]

\[
\beta = 3.12^{+1.47}_{-1.02}
\]

\[
\Phi^* = 1.12^{+0.04}_{-0.07} \times 10^{-5} \text{ Mpc}^{-3}
\]

L* smaller than derived at soft X-rays as the soft X-ray AGN population is less absorbed.

There are no bright Compton thick AGN population missed at low energy.

Hard X-ray surveys of local AGNs do constrain synthesis model of the XRB.

Gilli et al., 2008

Follow-up observations will reduce the uncertainty

M87 at hard X-rays

- For many years the hard X-ray emission of M87 appeared displaced by about 1°

- The University of Birmingham coded mask instrument (spacelab 2) provided the first high resolution image and an upper limit of $F(20-60) < 1 \times 10^{-11}$ erg/s/cm² (Hanson et al, 1990)

- Ginga scanning data provided a detection with a flux of $F(20-60) \sim 4 \times 10^{-11}$ erg/s/cm² (Takano & Koyama, 1991)

- RXTE did not detect any non thermal component with $F(20-60) < 3 \times 10^{-12}$ erg/s/cm² (Reynolds et al, 1999)

The INTEGRAL/ISGRI view:

- 300 ksec eff. exposure (1 Ms next year)

- Consistent with a point source (psf 6 arcmin)

- Position marginally (90%) consistent with M87.
What is it?

1. Thermal emission from Virgo
   - extract XMM spectra from concentric rings
   - fit with a thermal spectrum (vmekal, 2T in the inner 6’)
   - extrapolate between 20-60 keV
   ➔ thermal component is at most few % of the ISGRI detection

2. Nucleus and kpc jet
   - Nucleus: F(1-10 keV)~8 $10^{-13}$ erg/s/cm$^2$; $\Gamma = 2.23$
     extrapolates to F(20-60 keV)~ (4–6) $10^{-13}$ erg/s/cm$^2$
   ➔ nucleus is at most 5 % of ISGRI detection
   - similar argument on the jet knots (excepting HST-1 flare)
What is it?

3. HST-1

Since 2001 HST-1 features a huge flare monitored by Chandra F(0.2-6keV) increasing from $8 \times 10^{-13}$ to $4 \times 10^{-11}$ erg/s/cm². Spectral shape unclear because of pile-up. Γ_X = 2.4-2.6 has been derived. Continuous Clocking mode observation ➔ Γ_X = 2.7

→ for Γ_X = 2.7 the fluxes do not match
→ for Γ_X < 2.3 the fluxes could match, however the expected variability was not observed.

Harris et al (2006)
What is it?

4. Radio halo

The angular size of the non thermal radio halo (10 armin) is similar to the ISGRI psf

- add a hard X-ray powerlaw to the thermal component
- fit to the integrated XMM spectra extracted from rings
- extrapolate in 20-60 keV band

It works as long as $\Gamma < 2.5$:

- $\Gamma = 1.5 \rightarrow$ inner 3 arcmin
- $\Gamma = 2.0 \rightarrow$ inner 5 arcmin $\sim$ size of radio halo
- $\Gamma = 2.5 \rightarrow$ inner 13 arcmin

Could hard X-rays be IC emission?

Do we have a problem with the apparent offset?
Physics of the radio halo

Radio emission implies high energy electrons.

The likely seed photons for the IC emission is the IR stellar light:

$$U_{\text{bulge}} = \frac{L_{\text{bulge}}}{4\pi R_{\text{bulge}}^2} = 10 \left[ \frac{R_{\text{bulge}}}{10 \text{kpc}} \right]^{-1} \text{eV/cm}^3 \quad (U_{\text{CMB}}=0.25 \text{ eV/cm}^3)$$

The energy of the electrons IC scattering IR in 20-60 keV band is

$$E_{\text{e, IC}} \approx 300 \left[ \frac{0.1 \text{ eV}}{\epsilon_0} \right]^{1/2} \left[ \frac{\epsilon}{20 \text{ keV}} \right]^{1/2} \text{MeV}$$

These emit synchrotron at

$$\epsilon_{\text{sync}} \approx 100 \left[ \frac{E_{\text{e, IC}}}{300 \text{MeV}} \right]^2 \left[ \frac{B}{10 \mu \text{G}} \right] \text{MHz}$$

and we have

$$\frac{L_{\text{IC}}}{L_S} = \frac{8\pi U_{\text{rad}}}{B^2} \approx 4 \left[ \frac{U_{\text{rad}}}{10 \text{ eV/cm}^3} \right] \left[ \frac{B}{10 \mu \text{G}} \right]^{-2}$$

The integrated radio flux at 100MHz is $\sim 10^{-12} \text{ erg/s/cm}^2$

$\Rightarrow B \sim 5 \mu \text{G}$ consistent with other estimates & equipartition.

$\Rightarrow$ observed hard X-rays at a level which could be expected.

$$L_X + L_{\text{rad}} \sim 10^{42} \text{ erg/s} \sim 1\% \text{ mechanical energy}$$
Offset?

1. First the offset may not be real. We need (and will soon get) more INTEGRAL data.

2. Bulk of emission on the left of the radio halo

3. M87 oscillations:

From XMM pressure/entropy/abundance maps Simionescu et al (2006) have proposed that M87 oscillates at the center of the Virgo cluster.
A similar behavior was proposed by Churazov (2003) for Perseus (see also simulations by Ascasibar & Markevitch 2006).

Dynamical time scale: \( \frac{D}{v_{\text{virial}}} \sim \frac{20 \text{ kpc}}{500 \text{ km/s}} \sim 0.05 \text{ Gyr} \)

IC cooling time scale: \( t_{\text{IC}} \approx 0.1 \left[ \frac{U_{\text{rad}}}{10 \text{ eV/cm}^3} \right]^{-1} \left[ \frac{E_e}{300 \text{ MeV}} \right]^{-1} \text{ Gyr} \)

The electrons cool slowly, when compared to the path of M87

\( \rightarrow \) the IC emission may reveal the “foot-print” of M87