Radio AGN feedback on galaxy scales: What can Athena show us?

Beatriz Mingo
University of Leicester
Collaborators:
Mike Watson (Leicester)
Martin Hardcastle (Hertfordshire)
Judith Croston (Southampton / Cambridge)

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Jets and lobes in small sources

• Why?
  - RL phase affects environment dramatically: fundamental to understand timescales of SF triggering/quenching and AGN feedback

• Where?
  - Low z for max spatial resolution and S/N
    • Low power systems
    • Early stage high-power systems (less likely in spirals, but see e.g. Hota et. al. 2011)

• How?
  - X-rays + radio to study extended structure
Seyferts and Spirals

- 30+ known Seyferts with extended radio structures (e.g. Hota & Saikia 2006, Gallimore et. al. 2006)
  - Not all Seyferts are spirals!
  - Few examples of powerful radio galaxies in spirals (Hota et. al. 2011, Keel et. al. 2006)
  - Jets and lobes may not be directly visible but they may still be there...

- Jets and lobes in Seyferts are typically a few kpc long, radio cores are very weak (e.g. Middelberg 2004)
Bubbles and shocks in small sources

- Jet $\rightarrow$ ISM E transfer
  - Age $\sim 10^6$-$10^8$ yr
  - $E \sim 10^{56}$ erg, equiv to $\sim 10^5$ SN

- Overpressure, T jump $\rightarrow$ shocks
  - $M \sim 3$-$6$

- Energetics (Jet + lobes/bubbles + shock)
- Timescales
- Feedback, SF triggering/quenching
- Power/mass scaling
- Morphology dependence

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Centaurus A
(Kraft et al. 2003, Croston et al. 2009)
Markarian 6: Chandra/XMM

S0
Sy 1.5
D \sim 78 \text{ Mpc}
Lobes \sim 7.5 \text{ kpc}

Shock \sim 15\% \text{ flux 0.7-1.1 keV}
KT \sim 0.9 \text{ keV}
Mach number: 3.9 (+1.9 -1.0)
Total E (thermal + kinetic): 2.6-4.6 \times 10^{56} \text{ erg}
Timescale: 0.3-1.1 \times 10^7 \text{ years}
Variable nuclear obscuration
Markarian 6: Athena

NH \approx 3 \times 10^{23}
20 ks constrain kT with >90\% accuracy

NH \approx 2 \times 10^{22}
20 ks constrain kT with \approx 80\% accuracy

→ Possible to catch shocked gas with short exposures
(if we know what we are looking for...)

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Other candidates: NGC 6764

- The X-ray bubbles (~ 2kpc) are 2x more luminous than the starburst wind → jet-driven shock

- V~740 km/s, E~$10^{56}$ erg, t~$10^6$ yr

- Emission is not clearly edge-brightened, perhaps because of very dense ISM (Sy2 in SB barred spiral)

Croston et. al. 2008, Hota & Saikia 2006, Kharb et. Al. 2010
Other candidates: the Circinus Galaxy

Shock heating
\[ \frac{\rho_{\text{out}}}{\rho_{\text{shell}}} \rightarrow \frac{\Gamma + 1}{\Gamma - 1} = 4 \]

\[ M = \sqrt{\frac{4(\Gamma + 1)T_{\text{shell}}}{2\Gamma} + \frac{\Gamma - 1}{\Gamma}} \]

Synchrotron
\[ \nu_s = \frac{\gamma^2 e B}{2\pi m_e c} \]
\[ \tau = \frac{5 \times 10^8}{B^2 \gamma} \]

Photoionization
Hotspot
AGN (nearest Sy2)
Enhanced synchrotron (compression + B amplification)

Mingo et. al. 2012
Other candidates

- **NGC 1068** (Young et al. 2001)
  
  - $V \approx 690$ km/s, $E_{th} \approx 10^{54}$ erg ($< E_{kin}$)

- **M 51** (Terashima & Wilson 2001)
  
  - L (2-10 keV) $\sim 10^{41}$ erg/s

- **NGC 3079**
  
  - Coexistence of jet-driven and star-driven outflows (Cecil et al. 2001, Irwin & Saikia 2001)

- See also Hota & Saikia 2006
Shocks in radio galaxies: Centaurus A

- Original motivation: from min E arguments we know RG lobes have to drive shocks
- Thermal emission $\rightarrow$ shock conditions
- Pressure jump $\sim 10x$ near the nucleus $\rightarrow M\sim 2.8$, $V\sim 860$ km/s
- Best example of shocks, IC in the lobes
  - IC is elusive! E.g. in Circinus IC X-ray L is $\sim 100x$ smaller than the thermal L
See Croston, Sanders et al's Athena science paper (arXiv:1306.2323)
Power scaling

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>L 1.4 GHz W/Hz/sr</th>
<th>E_tot (erg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cen A</td>
<td>E</td>
<td>1.5x10^{23}</td>
<td>10^{57}</td>
</tr>
<tr>
<td>NGC 3801</td>
<td>E</td>
<td>1.2x10^{23}</td>
<td>2x10^{56}</td>
</tr>
<tr>
<td>M 51</td>
<td>Sb</td>
<td>1.5x10^{21}</td>
<td>&gt;10^{54}</td>
</tr>
<tr>
<td>Mrk 6</td>
<td>S0</td>
<td>1.7x10^{23}</td>
<td>3-5x10^{56}</td>
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<tr>
<td>NGC 6764</td>
<td>Sb</td>
<td>1.1x10^{21}</td>
<td>10^{56}</td>
</tr>
<tr>
<td>Circinus</td>
<td>Sb</td>
<td>2.2x10^{20}</td>
<td>2x10^{55}</td>
</tr>
</tbody>
</table>

That is 10^4-10^6 SN explosions! (assuming 10^{51} erg SN) → environment must be affected

e.g. in NGC 3801 this E corresponds to the total thermal E in the ISM within 11 kpc, and 25% of the E within 30 kpc (Croston et. al. 2007)
Conclusions

- Shocks and bubbles are common in Seyferts
  - Athena won't have the spatial resolution to find them, but we have already done that and know where to look!
  - X-IFU has the spectral resolution to help us determine abundances, shock speeds, characterise the external medium...

- X-IFU → Constraints on low and high power radio sources (even with reduced effective area)
  - Characterise AGN feedback from Sgr A* to powerful RL QSO