Nearby Galaxy Clusters with UVIT/Astrosat

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Astrosat Meeting on Baseline Science
Feb. 6-7, 2014
Indian Institute of Astrophysics, Bengaluru
Scientific Motivation

• Galaxy clusters are extreme environments in hierarchical structure formation.

• The present-day spatial distribution, internal structure, ages and chemical composition of their constitute galaxies (and other baryonic structures such as star clusters, UCDs, and intra-cluster light) can be used to determine their initial conditions and subsequent evolution in a $\Lambda$CDM universe.

• Unraveling these complex processes requires multi-wavelength observations from the UV to IR.

• Doing so for the distinct structural and kinematical components of galaxies requires sub-galaxy resolution.

• Combined with longer wavelength (optical and IR) data, the UV region can also be used to decouple the recent and long-term star formation histories of galaxies.

\begin{tabular}{|c|c|c|c|c|}
\hline
$z$ & $\Theta$ (kpc) & & & \\
\hline
 & $5^\prime$ & $1.4^\prime$ & $0.8^\prime$ & $0.15^\prime$ \\
\hline
20 Mpc & 0.52 & 0.15 & 0.08 & 0.015 \\
0.1 & 9.25 & 2.52 & 1.48 & 0.27 \\
0.5 & 30.6 & 8.59 & 4.89 & 0.92 \\
1.0 & 40.0 & 11.2 & 6.40 & 1.20 \\
2.0 & 41.8 & 11.9 & 6.68 & 1.28 \\
\hline
\end{tabular}
Baseline Science

- Key factors to consider in choosing baseline science programmes with UVIT:

1. high scientific impact!
   - programme must demonstrate UVIT’s unique capabilities relative to previous missions
     1. spatial resolution.
     2. sensitivity.
     3. SED sampling.

2. availability of supplementary data (optical through near-IR) for leveraging UVIT imaging.

3. availability of previous UV imaging (GALEX) for calibrations, cross-checks and performance verification.

4. opportunities for coordinated observations with Astrosat’s X-ray instruments (LAXPC, SXT, CZTI, SSM).

- Two possible (and scalable) baseline science programmes for nearby clusters:

  1. A UVIT/Astrosat Survey of the Coma Cluster (deep or shallow/complete)
  2. A UVIT/Astrosat Survey of the Virgo Cluster Core (deep or shallow/complete)
Possible Baseline Science: Nearby Galaxy Clusters. I. Coma
A UVIT Survey of the Coma Cluster

- Coma is the archetypal galaxy cluster and has been studied extensively at virtually all wavelengths. It is the most massive cluster in the nearby universe \((D \sim 100 \text{ Mpc})\), with \(\sigma = 1082 \text{ km/s}, M_{200} = 2 \times 10^{15} \text{ M}_\odot\), and \(R_{200} \sim 2.0 \text{ Mpc (1.2°)}\). Virtually every type of stellar system is represented in the cluster. The cluster shows evidence for environment quenching of galaxies (e.g., Smith et al. 2012).

- However, UV imaging has been limited to panoramic coverage with GALEX or pointed observations for a small number of HST fields. UVIT imaging would provide the definitive UV study of the cluster.

- UVIT targets are individual galaxies, including UCDs, but probably not globular clusters (whose luminosity function peaks at \(g \sim 28 \text{ AB mag}\)).

- The UVIT FWHM at the distance of Coma corresponds to \(\sim 730 \text{ pc}\), which is roughly the same as the effective radii of galaxies with stellar masses below \(M_* \sim 10^{9.5} \text{ M}_\odot\). In fact, galaxies will be marginally resolved (i.e., FWHM < \(D_e\)) down to \(B \leq 24.3\) or \(M_* \geq 5.7 \times 10^6 \text{ M}_\odot\).
A UVIT Survey of the Coma Cluster

Coordinates.

- DEC(J2000) = +27:58:50

Strategy.

Possibilities include: (1) a single deep (30,000 sec) exposure in the core, and (2) ~25 shallow (5000 sec) exposures to cover the rest of the cluster.

Instrumental Setup.

- NUVB2 (λc = 2200 Å, FWHM = 700 Å)
- CaF2 (passband = 1300–1800 Å)

These filters maximize throughput and optimize SED coverage. They also resemble the NUV (1750–2750 Å) and FUV (1350–1750 Å) bands of GALEX.
A UVIT Survey of the Coma Cluster

Opportunities for Coordinated Observations.

The cluster has been observed extensively at nearly all wavelengths, including X-rays (Einstein, ROSAT, Chandra, XMM, etc). The cluster contains a number of AGNs and a massive X-ray emitting ICM.

Supplementary Data.

An enormous amount of data exists for the cluster, including imaging from the HST Coma Cluster Treasury Survey. Other datasets include VLA, Spitzer/IRAC, Herschel, GALEX, SDSS, XMM, Chandra, Keck/DEIMOS, MMT/Hectospec, CFHT/WIRCAM, Subaru/SuprimeCam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Deep Core</th>
<th>Full Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>N point</td>
<td>1</td>
<td>~25</td>
</tr>
<tr>
<td>Area</td>
<td>0.2 (deg²)</td>
<td>4.5 (deg²)</td>
</tr>
<tr>
<td>NUV Filter</td>
<td>NUVB2</td>
<td>NUVB2</td>
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<tr>
<td>FUV Filter</td>
<td>CaF2</td>
<td>CaF2</td>
</tr>
<tr>
<td>NUV Exposure Time</td>
<td>30,000 sec</td>
<td>5,000 sec</td>
</tr>
<tr>
<td>FUV Exposure Time</td>
<td>30,000 sec</td>
<td>5,000 sec</td>
</tr>
<tr>
<td>NUV M&lt;sub&gt;AB&lt;/sub&gt;</td>
<td>26.2:</td>
<td>25.2:</td>
</tr>
<tr>
<td>FUV M&lt;sub&gt;AB&lt;/sub&gt;</td>
<td>25.7:</td>
<td>24.3:</td>
</tr>
<tr>
<td>Total Exp. Time</td>
<td>30,000 sec (14 orbits)</td>
<td>125,000 sec (57 orbits)</td>
</tr>
</tbody>
</table>
Possible Baseline Science:
Nearby Galaxy Clusters. II. Virgo
Virgo is the rich cluster nearest to the Milky Way (D = 16.5 Mpc). Virtually every UV mission has observed Virgo early in its lifetime.

Open questions include: (1) the UV luminosity function; (2) stellar populations in galaxies; (2) star formation, quenching and cluster infall; (4) hot stars in globular clusters, UCDs and galactic nuclei; (5) SED fitting and mass estimation for stellar systems.

Advantages: (1) the cluster’s proximity means that imaging to $m_{AB} \sim 25$ reaches past the globular cluster luminosity function turnover; (2) UVIT resolution corresponds to a physical scale of just 150 pc!

Complication: the cluster spans a huge area on the sky (~100 deg$^2$). Despite this, extensive UV coverage is available from GALEX.

Boselli et al. (2011)
Digression 1: Hot Stars in Virgo Globulars

- HST/STIS imaging of M87 globular clusters reveals some clear differences compared to MW clusters: i.e., larger populations of hot HB stars.
- This is important since some population synthesis models (e.g., Yoon et al. 2006) suggest hot HB stars are responsible for the colour bimodality of globular cluster systems.
Digression 2: Nuclear Star Clusters

NGC205 (HST/WFPC2)  
NGC205 (UVIT PSF)  
NGC205 (GALEX PSF)
• Pencil-beam surveys with HST (WFPC2, STIS, WFC3), Chandra, XMM, and VLA are available for numerous fields within the cluster. And wide-field X-ray coverage is available from ROSAT.
• But complete coverage with UVIT is not feasible as a baseline science programme.
Virgo as Seen by Astrosat

Virgo as Seen by Astrosat

A and B boundaries (Virgo Cluster Catalog; Binggeli et al. 1985)
UVIT and the NGVS Pilot Programme Field

• The central $2^\circ \times 2^\circ$ of Virgo has deep ugrizK CFHT imaging to $g = 25.7$ AB mag (10-sigma, point-source limit) from NGVS and NGVS-IR (Ferrarese et al. 2012, Muñoz et al. 2014).

• Deep FUV and NUV imaging from UVIT would provide SEDs over the entire FUV to NIR range. As many SED points as possible in the UV region is desirable.

• Targets include thousands of globular clusters (metal-rich and metal-poor), hundreds of galaxies, ~170 UCDs, and dozens of nuclei (nuclear star clusters).

Instrumental Setup.

- CaF2, Sapphire, Silica
- NUVN1, NUVB2, NUVB3, NUVB4, NUVN2
GC and UCD Colour Distributions in the Core of Virgo

Liu et al. (2014)
UVIT and the NGVS Pilot Programme Field

Opportunities for Coordinated Observations.

M87 itself contains one of the largest known super-massive black holes (a prodigious emitter of X-rays). Chandra has also revealed hundreds of point-sources associated with the M87 globular clusters; these are likely LMXBs. In addition, the core of the cluster contains a large numbers of low-mass galaxies, which themselves may show X-ray emission in their cores. Finally, M87 is located close to the dynamical center of the Virgo cluster, which contains \( \sim 3.5 \times 10^{11} \) solar masses of X-ray gas at a temperature of \( \sim 2.5 \) keV.

Warnings.
The nucleus of M87 is a strong emitter at X-ray wavelengths. A bright star is located 5.7' to the north of M87.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Central Field (Deep)</th>
<th>Complete Coverage (Shallow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{point}</td>
<td>1</td>
<td>\sim 30</td>
</tr>
<tr>
<td>Area</td>
<td>\sim 0.2 (deg^2)</td>
<td>4 (deg^2)</td>
</tr>
<tr>
<td>NUV Filters</td>
<td>CaF2, Sapphire, Silica</td>
<td></td>
</tr>
<tr>
<td>FUV Filters</td>
<td>UVN1, NUVB2, NUVB3, NUVB4, NUVN2</td>
<td></td>
</tr>
<tr>
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<td>$5 \times 240$ sec</td>
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<tr>
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<td>$3 \times 400$ sec</td>
</tr>
<tr>
<td>NUV M_{AB}</td>
<td>\sim 25.9:</td>
<td>\sim 22.7:</td>
</tr>
<tr>
<td>FUV M_{AB}</td>
<td>\sim 25.5:</td>
<td>\sim 22.0:</td>
</tr>
<tr>
<td>Total Exp. Time</td>
<td>\sim 75,000 sec (34 orbits)</td>
<td>\sim 36,000 sec (16 orbits)</td>
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