An X-ray view of the hot circum-galactic medium (CGM)

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Outline

1. What we know about the hot CGM?
2. What we still don’t know?
3. What could we do with future X-ray missions?
1.0. Key science related to the hot CGM

Mass/baryon/metal and energy budget of galaxies

How much mass/baryon/metal and energy are expected v.s. How much are detected

Other key science:

How the CGM is connected to the star formation?

How the galaxies coevolve with their ecosystem?
1.0. Key science related to the hot CGM

Mass/baryon/metal budget of galaxies

= baryon/(baryon+dark matter)


Energy budget of galaxies

X-ray

Radio

Energy detected in different phases of the CGM

Expected supernovae energy injection rate
Energy budget of galaxies

Energy sources:
(1) AGN
(2) Gravitational energy of the infall gas in the dark matter halo
(3) Radiation from young stars
(4) Young stellar wind
(5) Supernovae: Type Ia+ core collapsed (CC)

Inside the galaxy (in the ISM):
(1) IR continuum reprocessed by dust
(2) UV, optical, IR line emission reprocessed by cool gas

Out of the galaxy (in the CGM):
(1) Thermal energy of hot gas (radiated via X-ray) ~1%<sub>ESN</sub>
(2) Kinetic energy of global motion of hot gas (pressure driven adiabatic expansion) <1%<sub>ESN</sub>
(3) Turbulent energy of small scale motion of hot gas <0.1%<sub>ESN</sub>
(4) Kinetic energy of cold gas outflow <1%<sub>ESN</sub>
(5) Radiative cooling of cool gas (peaked in UV emission lines) ~5%<sub>ESN</sub>
(6) Cosmic ray (CR) ~5%<sub>ESN</sub>
(7) Large scale magnetic field <5%<sub>ESN</sub>

Total energy detected in the CGM: E<sub>CGM</sub><20%<sub>ESN</sub>

Based on current observations!
1.1. Astronomy: Extended diffuse soft X-ray emission is ubiquitous around nearby galaxies

M82 Starburst in the nuclear region
NGC891

Star formation region spread over the disk
NGC3115: Isolated early-type galaxy with almost no star formation.
NGC4594

Isolated early-type galaxy with almost no star formation
NGC4342

Small quiescent galaxy in a galaxy cluster
NGC 4438

Interacting galaxy pair in a galaxy cluster
Soft X-ray emitting hot CGM is ubiquitous around galaxies!

X-ray properties of the hot CGM is different in different types of galaxies!

1.2. **Statistics**: X-ray properties of the CGM are different in different types of galaxies


Sample still small. Cannot well determine relationships for different subsamples.

**Graph:**
- **X-axis:** $M^*$ (10^{10} M_{\odot})
- **Y-axis:** $L_X$ (10^{38} ergs s^{-1})
- **Legend:**
  - Starburst galaxies
  - Non-starburst disk galaxies
  - Elliptical galaxies

Outline

• 1. What we know about the hot CGM?
• 2. What we still don’t know?
• 3. What could we do with future X-ray missions?
2.1. **Physics**: What is the physical, chemical, and dynamical properties of the hot CGM?

Grating X-ray spectra.

Soft X-ray emission dominated by **strong emission lines** from different components.

Photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$

Energy (keV)

Wavelength (Å)

Photon cm$^{-2}$ Å$^{-1}$ Å$^{-1}$

CCD imaging spectra

grating spectra
87% of the OVII 22Å and 54% of the OVIII 19Å emissions are produced by charge exchange (CX), instead of thermal plasma!
2.2. **Cosmology**: What is the total mass/baryon/metal and energy content of the hot CGM?

An example on the hot baryon content

![Stacked Hot Gas Intensity Profile of CGM-MASS Galaxies](image)

**Li et al., 2018, ApJL, 855, 24**
~26% of the expected baryons are detected in stars and the hot CGM.
Where are the missing baryons?


Different phase or different place?
Outline

1. What we know about the hot CGM?
2. What we still don’t know?
3. What could we do with future X-ray missions?
• **Larger sample** to study the dependence of CGM properties on **various** galaxy properties for **various** types of galaxies.

• **High resolution spectra** \((E/\Delta E>500;\)** microcalorimeter for imaging spectroscopy or **grating** for absorption line studies) for the study of the **physical, chemical, dynamical** states, and total **energy budget** of the hot CGM.
Other mission concepts of focusing X-ray telescopes: **AXIS, Super DIOS**

- **Larger sample** to study the dependence of CGM properties on various galaxy properties for various types of galaxies.

- **High resolution spectra** \((E/\Delta E>500; \text{microcalorimeter for imaging spectroscopy or grating for absorption line studies})\) for the study of the physical, chemical, dynamical states, and total energy budget of the hot CGM.

- **Deep narrow-band imaging** and/or stacking of large sample to probe the radial distribution, outermost extension, total mass/baryon/metal and energy content of the hot CGM.
A TES spectrometer optimized for soft X-rays
- Energy range: 0.1-2 keV
- 60x60 pixel array, with 2 eV energy resolution
- 12x12 central sub-array with smaller pixels, optimized for absorption line spectroscopy with sub-eV resolution below 1 keV

High throughput X-ray optics with large FoV
- Effective area: $A_{\text{eff}} > 500 \, \text{cm}^2$

### Table

<table>
<thead>
<tr>
<th>Name</th>
<th>d (Mpc)</th>
<th>v (km/s)</th>
<th>$r_{\text{virial}}$ (deg)</th>
<th>$\Delta E$ (eV) @0.6keV</th>
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For detecting absorption lines from bright point-like sources, the instrumental figure-of-merit (FoM) is:

\[ FoM = RA_{\text{eff}} \]

<table>
<thead>
<tr>
<th>Mission</th>
<th>Instrument</th>
<th>Technology</th>
<th>R\textsubscript{@0.6 keV}</th>
<th>A\textsubscript{eff} \textsubscript{@0.6 keV (cm\textsuperscript{2})}</th>
<th>FoM \textsubscript{x1000}</th>
<th>EW limit (mA)</th>
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<td>10</td>
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<td>5000</td>
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<td>&gt;5000</td>
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<td>&gt;20000</td>
<td>&lt;0.8</td>
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For detecting **emission lines** from **extended sources**, the instrumental figure-of-merit (FoM) is:

$$FoM = RA_{\text{eff}} \Omega_{\text{FOV}}$$

<table>
<thead>
<tr>
<th>Mission</th>
<th>Instrument</th>
<th>Technology</th>
<th>$R_{\text{@0.6 keV}}$</th>
<th>$A_{\text{eff @0.6 keV (cm^2)}}$</th>
<th>$\Omega_{\text{FOV}}$ (deg$^2$)</th>
<th>FoM</th>
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<td>Calorimeter</td>
<td>300</td>
<td>500</td>
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<td>150000</td>
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But the hot CGM is also traced by the **SZ (Sunyaev–Zeldovich) signal** and some **UV emission lines from high ions** (Mg X, Ne VIII, etc.)
Multi-wavelength survey of the multi-phase CGM

- $\gamma$-ray
- Soft X-ray
- UV
- Optical
- near-IR
- mid/far-IR
- mm/submm
- Radio
- CR
- hot CGM
- WHIM
- stars/gas
- PAH/gas
- dust/gas
- molecular gas
- atomic gas/CR/B

Monochromatic Luminosity, $\nu L_\nu$ [L$_\odot$]

- 10^9
- 10^8
- 10^7
- 10^6
- 10^5
- 10^4
- 10^3
- 10^2
- 10^1
- 10^0

Polarization fraction [%]

- 1000
- 100
- 10
- 5
- 1

Wavelength, $\lambda$ [\mu m]

- 0.1
- 1
- 10
- 100
- 1000
- 10^4

Extinction ($p/\tau$)

- $E_{\perp} / B_0$
- $E_{\parallel} / B_0$

Emission ($P/l$)

- Thermal dust emission
- Submm excess?
Summary

What we know and what we don’t know?

• Extended soft X-ray emission is ubiquitous around galaxies.  
  Astronomy 😊
• CGM X-ray properties depend on the galaxy properties in different ways for 
  different types of galaxies.  
  Statistics 😞
• Soft X-ray emission is dominated by various emission lines tracing different 
  physical processes.  
  Physics 😱
• The total mass/baryon/metal and energy content of the hot CGM is still poorly 
  constrained.  
  Thank you very much!  
  Cosmology 😨

What is the future?

• Larger sample for statistical analysis of different types of galaxies.
• High resolution spectra for the study of the physical, chemical, dynamical 
  states of the hot CGM.
• Deep narrow-band imaging and stacking of large galaxy sample probing 
  the radial distribution, outermost extension, total mass/baryon/metal and 
  energy content of the hot CGM.