The bright side of galaxy clusters

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11/02/2015

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Overview

1 Motivation: study of galaxy clusters

2 Synthetic X-ray observations
   - PHOX: photon X-ray simulator

3 Results & applications
   - Reconstruction of ICM thermal structure
   - The ICM velocity structure
   - Scaling laws among global properties

4 Summary

5 Further applications: AGN emission with PHOX
Motivation: study of galaxy clusters

Why galaxy clusters?

- Largest gravitationally-bound structures in the Universe
- Masses of $\sim 10^{14} - 10^{15} \, h^{-1} M_\odot$, sizes of $\sim$ few Mpc
- Potential well dominated by dark matter (DM)
- Comprise thousands of galaxies
- Most of the baryonic matter is in the form of hot, diffuse gas (ICM) with $T \sim 10^7 - 10^8$ K:
  - GCs are very bright, extended sources in the X-rays (bremsstrahlung + metal emission lines)

→ Use ICM observable properties (optical; radio; X-rays; lensing; SZ-effect) to trace the invisible ones
→ reconstruct cluster structure and employ clusters for cosmology & astrophysics!

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X-rays allow to investigate several issues, e.g. can be used to weight clusters. Simplest assumption:

- gas traces DM potential well
- gas is in hydrostatic equilibrium

\[ \frac{1}{\rho} \frac{dP}{dr} = -\frac{GM}{r^2} \]

- + spherical symmetry
- + only thermal pressure support

... then:

**Hydrostatic mass**

\[
M(< r) = -\frac{k_B T_{\text{gas}}}{G \mu m_p} \left( \frac{d \ln \rho_{\text{gas}}}{d \ln r} + \frac{d \ln T_{\text{gas}}}{d \ln r} \right)
\]
Nature is more complex

Not all clusters are simple to model...

Abell 2589; Perseus cluster; Bullet cluster.
Motivation: study of galaxy clusters

Maughan+ (2011)

Mazzotta+ (2004)

Lau+ (2009)

Rasia+ (2012; 2014)

What is the origin of these features?
Are the assumptions reliable?

What about...

- ... the complexity of the ICM thermal structure?
- ... the effects of non-thermal motions in the ICM?
- ... the effects of the cluster dynamical state?
- ... the deviation from the spherical symmetry?
- ... the intrinsic effects due to the observational method (e.g. for X-rays)?
- ... the differences in numerical/observational results?
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**Bridging numerical simulations to X-ray observations**

**Simulations**

- Cosmological hydrodynamical simulations of large-scale structures from which cluster catalogs are extracted, or zoomed re-simulations of single clusters
- Eulerian/Lagrangian approach — simulations performed with the SPH code Gadget-2/3
- Gravity (to describe DM) + hydro (for baryonic matter):
  adiabatic runs, or including additional physics (gas cooling, star formation, metal enrichment, feedback processes from SNe winds and AGNs)
- **ADVANTAGE:** direct access to 3D intrinsic properties as well as to evolution in time

**X-ray simulators**

**EXAMPLES:** X-MAS (Gardini+ 2004; Rasia+ 2008); XIM (Heinz+ 2009); etc.

**GOAL:** obtain observable-like quantities out of simulations that resemble as faithfully as possible those extracted from real X-ray observations.
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PHOX: X-RAY EMISSION FROM HYDRO-NUMERICAL SIMULATIONS

**Unit 1**
Generate an ideal cube of photons, sampling the model X-ray emission spectrum calculated for every emitting (gas) element.

**Unit 2**
Project along the l.o.s. and add Doppler-shift to photon energy due to l.o.s. motion (of the emitting element); select a sub-region of the 3-D photon cube.

**Unit 3**
Convolution with the instrumental response: choose an instrument (account for FoV, quantum efficiency, effective area and energy resolution) and assume a realistic exposure time.

V. Biffi et al. (2012)
Observing simulated galaxy clusters with PHOX: a novel X-ray photon simulator

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A NEW X-RAY PHOTON SIMULATOR

Each gas element ~ single-T emitting plasma

Emission in the X rays: spectrum → photons

box of photons

hydro-simulation

\[(x, v)_i\]

\[(n, T, Z)_i\]

mock observation
ICM thermal structure

ICM often has a multi-phase structure: multi-temperature fitting can help to constrain its thermal components: $K_{APEC} \propto E.M. = \int n_H n_e dV$

- 2 simulated clusters with different thermal structures
- Synthetic X-ray observations with Suzaku: spectra
- Multi-$T$ spectral modelling (5 fixed-$T$ APEC components): reconstruct ICM temperature distribution

Biffi et al. (2012); simulations by K. Dolag.

X-ray obs: Peterson+ (2003); Kaastra+ (2004); recent study by Frenk+ 2013.
Theoretically, e.g. from simulations, one can define different ICM “temperature” values: there is a bias between the X-ray temperature and the “true”, dynamical one ($T_X < T_{mw}$).

The complex multi-temperature structure of the ICM can also bias $T_X$ when a single-$T$ fit is performed.

$$T_{sim} = T_w = \frac{\sum_i w_i T_i}{\sum_i w_i}$$

Biffi, Sembolini et al. (2014); subsample of MUSIC-2 clusters simulated with the SPH code Gadget.
Estimating the ICM temperature: bias(es)

The presence of different thermal components (especially cold clumps) in the ICM might also depend on numerics...

- problems for standard SPH technique to treat gas mixing
- addition of *artificial conductivity* term (Valdarnini 2012)
- improved gas mixing, suppression of cold gas component
- study on a set of 8 simulated clusters with different dynamical states

The numerical approach itself can have an impact in shaping the ICM thermal (and dynamical) structure → effects mirrored by mock X-ray properties.

* improved SPH (artificial viscosity & conductivity) also impact gas velocity field
* **sims**: gas velocity field measurable *directly*
* **X-ray obs**: derivable from broadening of heavy-ion (e.g. Fe) emission lines — *BUT* high spectral resolution required...

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**ATHENA**
THE ASTROPHYSICS OF THE HOT AND ENERGETIC UNIVERSE

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energy range: 0.3–12 keV
spectral resolution: 2.5 eV @ 6 keV (X-IFU)

http://www.the-athena-x-ray-observatory.eu/
Results & applications

ICM velocity diagnostics & scaling relations

Deviations from self-similar appearance of clusters can be due to the presence of non-thermal motions in the ICM!

Biffi et al. (2013); subsample of simulated clusters from the Magneticum simulation (K. Dolag).

\[ \frac{\sigma_v}{\sigma_{\text{thermal}}} = \text{amount of non-thermal motions relative to thermal ones} \]

- Mimick expected performance of up-coming X-ray high-resolution spectrometer: e.g. **Athena** ↔ resolve non-thermal broadening of Fe emission line (e.g. @6.7 keV)
- Possibility to check against simulation the inferred gas velocities
- Relate cluster position in the \( L_X - T_X \) plane to amount of non-thermal ICM motions
**Results & applications**

**Scaling laws among global properties**

$L_X - T_X$ RELATION

Biffi, Sembolini et al. (2014); subsample of MUSIC-2 simulated clusters.

- **Large cluster sample:** better constraints on scatter
- **Quantities derived with observable-like approach:** more faithful comparison to obs.
- **Sims:** shallower slope and higher normalization (temperature bias + lack of AGN feedback treatment in these sims)
- **Differences depending on cluster dynamical state**

Physical processes treated in the simulation & estimation of observables from simulated clusters are both important in comparing against observations.

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The bright side of galaxy clusters  

11/02/2015 16 / 26
Results & applications

Scaling laws among global properties

SZ/X-ray scaling relations (I)

Biffi, Semololini et al. (2014); subsample of MUSIC-2 simulated clusters.

- Observational approach introduces additional scatter in the relations
- \( L_X \) is particularly sensitive to the thermo-dynamical structure of the ICM
- Observed deviation from self-similarity

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SZ/X-ray scaling relations (II)

Biffi, Sembolini et al. (2014); subsample of MUSIC-2 simulated clusters.

\[ Y_{\text{SZ}} \propto M_{\text{g,500}} T_{\text{X}} \]

SZ-effect and X-ray emission are sensitive to ICM temperature in a different way: they can be combined to minimize the relation scatter — deviations from 1:1 depend on thermal structure.
Study the ICM in clusters to constrain (i) statistical properties and (ii) deviations from theoretical expectations;

Use cosmological simulations to study directly intrinsic 3D properties (thermal structure, gas velocity field, metallicity), dynamical state, redshift evolution;

Generate mock X-ray properties from simulations to

1. compare against observed clusters in a more proper way,
2. constrain the numerical modeling,
3. help the interpretation of the underlying physics, and
4. possibly predict the observational achievements of up-coming X-ray instruments.
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**X-ray emission from the ICM AGNs**

PHOX for ICM emission:

- use (hot) **gas** particles in the simulation belonging to ICM;

- consider temperature, density and metallicity (average or with specified chemical abundances);

- X-ray model spectrum for *hot diffuse plasma*: **APEC** (from XSPEC package).
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**PHOX for AGN emission**

$\rightarrow$ Partially modify PHOX-Unit 1:
- Sims w/ AGN feedback: construct ideal X-ray spectrum $\forall$ **BH-particle**;
- particular spectrum shape: power-law
  - luminosity from BHAR, following Churazov+2005
  - assumption for:
    - $L_{\text{rad}} \rightarrow L_{\text{SHR}}$ and $L_{\text{HXR}}$
  - $L_{\text{SHR}}$ and $L_{\text{HXR}}$ + power-law spectrum $\rightarrow$ constraints on spectral parameters
Further applications: AGN emission with PHOX

+ standard PHOX procedure:

- sample spectrum with discrete number of photons;

- collect all photons from all BH-particles in a 3-D box associated to sim. output;

- similarly to ICM photon cube: select spatial sub-region, project along l.o.s. and convolve with a real instrument characteristics.
Further applications: AGN emission with PHOX

→ Study the contribution from the central AGN to the global ICM luminosity

$L_{ICM} - T_{ICM}$

$L_{AGN} - T_{ICM}$

H. R. Russel et al. (2013)

R. Mittal et al. (2011)
Further applications: AGN emission with PHOX

Preliminary

* tested for a few clusters and central AGNs with PHOX, to be done for the sample — e.g. investigate performance of Athena at high-redshift
Thanks!

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\[
\frac{L_{\text{rad}}}{L_{\text{Edd}}} = \begin{cases} 
\varepsilon_r \left( \frac{10 \dot{M}}{\dot{M}_{\text{Edd}}} \right), & \text{if } BHAR > 0.1 \\
\varepsilon_r \left( \frac{10 \dot{M}}{\dot{M}_{\text{Edd}}} \right)^2, & \text{if } BHAR < 0.1 
\end{cases}
\]