From distant galaxy clusters ... to the Chandra Deep Field South ... from JHU to ESO

Piero Rosati
(Università di Ferrara, IT)
Cluster “evolution” in the early-mid 90s

- Confusion reigned in the community about evolution of cluster abundance
- “Tension” on cluster evolution from X-ray (EMSS, Gioia et al. 90) and (small area) optical surveys (Couch et al. 1991, Postman et al. 1996, Carlberg et al. 1997)
- ROSAT mission (1990): great new opportunities for cluster surveys
- Motivation: cluster abundance and correlation function to measure $\Omega_M$ and $\sigma_8$ (Bahcall et al. 1997,1998)
Cluster detection methodology on ROSAT data

- Riccardo’s idea for my thesis (JHU, 1991): search for distant clusters in ROSAT data
- The first idea to use wavelet detection algorithms in X-ray astronomy was Riccardo’s!

From Sonar data processing technique.. to extended X-ray emission from clusters..!

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- ROSAT Deep Cluster Survey (RDCS): searching for extended sources serendipitously in ROSAT deep pointed observations (JHU then ESO)
  - Co-supervision by Colin Norman @ JHU
- >100 candidates clusters
- Intense follow-up program at ESO La Silla and KPNO (1994-2000)
Cluster “evolution”: the solution in the late 90s

The ROSAT Deep Cluster Survey: The X-Ray Luminosity Function out to $z = 0.8$

Piero Rosati, Roberto Della Ceca, Colin Norman, and Riccardo Giacconi

Received 1997 August 7; accepted 1997 October 28; published 1997 November 14

- No significant evolution of the cluster abundance out to $z \approx 1$
- Only hint of modest evolution of most massive clusters

Cluster number counts

Cluster X-ray Luminosity Function to $z \approx 1.2$
The population of distant clusters and cosmology

RDCS (as of Aug 2000)
EMSS (Gioia & Luppino, 94)
CfA: (Vikhlinin et al. 98)

37 at $z > 0.5$
10 at $z > 0.8$
4 at $z > 1$

Cosmology with RDCS

Empirical $L_X$-$M$ relation
$\Delta_{M-L_X} = 45\%$

$\Omega_M$

Borgani et al. 98
Rosati, Borgani, Norman 2001
The population of distant clusters and cosmology

Massive ($6 \times 10^{14} M_\odot$) cluster at $z=1.24$
(RDCS1252, Rosati et al. 04)

ROSAT (16 ksec)  
XMM (137 ksec)  
CHANDRA (188 ksec)

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(RDCS1252, Rosati et al. 04)

Borgani et al. 98
Rosati, Borgani, Norman 2001
Distribution of baryons and DM in a distant cluster (z=1.24)

- Weak Lensing with HST/ACS
- Rosati et al. 04, Lombardi et al. 05, Lidman 2005, Demarco et al. 07
- K-band img with VLT/ISAAC
- Spectroscopy with VLT/FORS2
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Rosati et al. 04, Lombardi et al. 05
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- K-band img with VLT/ISAAC
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Fe in ICM at z>1
Clusters at $z > 1$ part of multi-$\lambda$ campaign

Rosati et al. 02 (collab. with A.Stanford, P.Eisenhardt)
To solve definitely the problem of cluster formation and evolution, 
a Wide Field X-ray Telescope is needed

"We have developed optical designs to search efficiently for distant X-ray clusters"

Science driver: "survey for distant clusters \((z>1)\) with an Explorer satellite"

Polynomial optics design: 1 deg\(^2\) with a flat \(~5\)" PSF over the entire field
in other words an "X-ray Schmidt telescope", "no more difficult to fabricate than existing mirrors"
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Merit function to maximize

$$M = \sqrt{\left( \int \sigma^2 \, d\theta \right) / \left( \int \sigma \, d\theta \right)}$$

[See Pareschi’s talk]

![Graph showing FOV vs. RMS Spot Size](image)

![Graph showing Half Energy Width vs. Off-axis Angle](image)
Wide Field X-ray Telescope
(see talks by Chincarini, Gilli, Pareschi)

- NASA-Explorer Proposal in 1995 (PIs: Giacconi, Burg)
  - Basically turned down on the basis of a *prejudice* which dominated the theoretical and observational community in the early-mid 90s…
- Other attempts with ESA/ASI/NASA until 2002 not successful

Regarding your point that WFXT could provide an unbiased survey for clusters of galaxies, to help understand the development of structure in the early universe, the peer panel felt that the proposal did not adequately address the possibility that cluster evolution may be significant at z = 0.3 and more so out to z = 0.5. Estimates in the proposal of the number of sources were based upon the absence of evolution, despite recent publications (including one by some of the Co-Investigators) that suggest the presence of evolution at most redshifts. In the opinion of the reviewers, few clusters would be seen at z greater than 0.5 to 0.75 if evolution is, in fact, important. The result
Wide Field X-ray Telescope: 2011 design

- Grasp = (A·Ω) = 2-3 order of mag advance over existing or planned missions
- Wide and Deep: incomparably vast survey volume for clusters and AGN at high-z
- Physical source characterization for large samples, no need of optical follow-up
- M-class mission cost envelope, feasible and affordable mirror technology

"As always I love to quarrel with you, even if some times you are right." (RG: Nov 2007)
WFXT end-to-end sky simulations

$F_{[0.5-2 \text{ keV}]} = 2 \times 10^{-16} \text{ erg/cm}^2/\text{s (5σ)}$
WFXT end-to-end sky simulations

- ~3 × 10^5 clusters, 20,000 at z > 1!
- ~20,000 with redshift and temperature!
- Synergy with SZ surveys

~10^7 AGN, >1000 at z > 6 (first SMBH)

→ see R. Gilli’s talk

Expected number of clusters at z > 1

Santos et al. 08

The bullet cluster at high-z

F_{0.5-2 keV} = 2 × 10^{-16} erg/cm^2/s (5σ)
Chandra Deep Field selection, planning and execution

- Search for a “South Galactic Hole”, like the Lockman Hole ($N_H=0.6\times10^{20} \text{ cm}^{-2}$)
- No bright stars ($<14$ mag), no bright X-ray sources from RASS
- VLT should play a central role in the follow-up observations
- Down selection in March 1998: “we will make glamour in an another field…”
- First imaging with VLT with the Test Camera and FORS1 (Gilmozzi PI)
First 120 ksec Chandra observations (Oct-Nov 99):
- 160 sources, $F_{\text{lim}} = 2 \times 10^{-16}$ [0.5-2 keV], $2 \times 10^{-15}$ [2-10 keV] cgs
- resolving 60-80% of 2-10 keV XRB

Straightforward identification of counterparts on VLT/FORS1 imaging

First spectroscopic ID with VLT (2000)
First results: VLT spectroscopic follow-up

z=1.218 + HST/WFPC2 campaign prior to ACS (Schreier et al. 2001)

Giacconi et al. 2002

z=0.72

13 March 2001

Chandra and the VLT Jointly Investigate the Cosmic X-Ray Background

z=3.7 Type II QSO

Giacconi et al. 2002

Group at z=0.72
The 1-Msec exposure

• ~350 sources \( f_{\text{lim}} = 5 \times 10^{-17} \) [0.5-2 keV], \( 5 \times 10^{-16} \) [2-10 keV] cgs)

• Up to 90% of the 0.5-2 keV XBR resolved

• First redshift distribution of Type-1/2 AGN \( \rightarrow \) XRB models

• From 1 to 7 Ms (Brandt et al.): see Roberto Gilli’s talk
The Impact and Legacy of the CDFS

- CDFS+GOODS (PI: Cesarsky): first experiment of Public Surveys at ESO with contributions from the user community
- VLT U+NIR imaging and panoramic spectroscopy to complement HST data
- Public Advanced Data Products of CDFS stimulated rapid and large scientific exploitation (many high-impact publications), attracted more programs...

Great Observatories Origins Deep Survey • CDF-S
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, The GOODS Team and M. Giavalisco (STScI) • STScI-PRC03-18a
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~4000 redshifts

Szokoly et al., Vanzella et al., Popesso et al., Balestra et al., Silverman et al. (2006-2010)
The Impact and Legacy of the CDFS @ESO

- CDFS stimulated one of the most intense multi-λ, multi-observatory campaign in astronomy (e.g. VLA survey (PI: K. Kellermann), IR, submm)
- Similar initiatives in other fields launched: COSMOS, CANDELS,…
- Use of ESO facilities on CDFS:
  - 300 independent VLT programs (1999-2018) totalling to 540 nights ➔ 10% of VLT science time over 20 years!
  - ESO Survey telescopes (WFI@2.2, VST, VISTA): ~130 nights
  - ALMA: 220 h, 77 programs (~10 independent programs per year)
- 560 refereed articles from CDFS data, 33000 citations (x 2 with GOODS-S)
From the CDFS to the Hoary Deep with Hubble
From the CDFS to the Hoary Deep with Hubble

Ultra Deep Field
From the CDFS to the Hoary Deep with Hubble

...so much for the “glamour”
Cluster evolution 25 years later: evolution occurs further back in time ($z \gg 1$)
Nature was indeed more imaginative than us..

- Cluster evolution 25 years later: evolution occurs further back in time ($z \gg 1$)
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"..understanding Nature requires skill in providing discovery space and care in listening to its replies"

(RG: Sep 2010)

Humble before Nature with a vision, and a plan..!

- Metal enrichment of ICM nears completion
- Star-formation quenched in cluster cores
- Morphology-density relation and galaxy red-sequence emerge

(Rosati, NatAstro, Dec 2018)
Cluster evolution 25 years later: evolution occurs further back in time ($z \gg 1$)
Nature was indeed more imaginative than us..

WFXT (RG: “my best idea”) will preserve its vast discovery power even in 2030:
X-ray surveys to catch up with area/sensitivity of future surveys (LSST, Euclid, SKA,…)

Humble before Nature with a vision, and a plan..!

“..understanding Nature requires skill in providing discovery space and care in listening to its replies”

(RG: Sep 2010)
From my letter to Mirella in January:

…Besides the unparalleled scientific guidance I received, I keep precious record of his ethical principles for our profession and the role it should have in society. All these memories have now become a treasure for me, which I will try to pass on to young generations of scientists.

Retrospective, Science (Jan 2019)