OBSERVING THE FRONTIER CLUSTERS WITH CHANDRA

C. JONES FOR THE CHANDRA FRONTIER CLUSTERS TEAM

Special thanks to Reinout van Weeren - lead for radio studies
Georgiana Ogrean (MACS0416), Felipe Santos (MACS0717),
W. Forman, S. Murray, A. Zitrin, A. Vikhlinin, L. David, E. Churazov,
S. Randall, R. Kraft, E. Bulbul, P. Rosati, A. Goulding, A. Bonafede, B.

Primary Goals
• improve understanding of merger process
• map gas temperature and pressure and identify shocks
• compare radio relics and halos with cluster merger properties to
  understand particle acceleration
• understand merger effects on galaxy evolution
• characterize dark matter halos to $10^{13} \text{ M}_{\odot}$

Observation Status
Results
• A2744 mergers and jellyfish (Owers et al. 2011, 2012)
• MACS0717 lensed radio and X-ray sources (van Weeren et al.
  2014 in prep)
Chandra Observing Status

Abell 2744 ($z=0.308$) - 125 ks COMPLETE

MACSJ0416.1-2403 ($z=0.396$)
193 ks done; 107 ks (Dec 2014)

MACSJ0717.5+3745 ($z=0.545$)
243 ks COMPLETE

MACSJ1149.5+2223 ($z=0.543$)
140 ks done; 232 ks (Jan 2015)

Future
Abell S1060 (RXCJ2248.7-4431) ($z=0.348$) 27 ks
Abell 370 ($z=0.375$) 95 ks

Deep radio observations lead by R. van Weeren
Cluster growth through mass accretion

1) “Steady” infall of matter from filaments
2) Infall of groups
3) Major mergers

In MACS0717 all of the above- Talk by Felipe Andrade-Santos
Clusters as cosmic telescopes

MACS J0717.5+3745 - Radio sources

Deep JVLA observations

1.0-6.5 GHz in A and B configurations

8 sources with multiplication factors >2

Most are likely star forming galaxies

R. van Weeren et al 2014 (in prep)
MACS0717 z>1 lensed radio sources
van Weeren et al. 2014 (in prep)

$S = 18 \, \mu Jy$
SFR $\sim 9 \, M_\odot \, yr^{-1}$

$z=1.1$

Factor > 7 magnification
Most detected sources have lower magnification

$S = 21 \, \mu Jy$
SFR $\sim 18 \, M_\odot \, yr^{-1}$

$z=1.4$

$\frac{\dot{M}_*}{M_\odot yr^{-1}} \approx 4.5 \left( \frac{\text{GHz}}{\nu} \right)^{-\alpha} \frac{L_\nu}{10^{22} \, \text{W Hz}^{-1}}$. 

Clusters as cosmic telescopes – study the faint radio source population at the level otherwise only possible with the SKA
Red = X-ray/optical
Black = X-ray/radio/optical
Blue = X-ray

MACS J0717.5+3745

243 ks
80K source counts

MACSJ0416.1-24.3 \( z=0.397 \) 193 ks Chandra

Classed as actively merging, after the primary collision, based on 16 ks Chandra (Mann & Ebeling 2012)

Determined to be either pre-merger or post-merger based on 53 ks Chandra, plus galaxy spectroscopy and lensing analysis (Jauzac et al. 2014)

Merger state determined from our deep Chandra observations (talk by Georgiana Ogrean)

Also CLASH Cluster (Postman et al.)
Abell 2744 (z=0.308) 125 ks Chandra Complete

X-ray luminous ($10^{46}$ erg/s) and hot (9 keV)
Major post core crossing merger

Owers et al. 2011
Abell 2744 (z=0.308) 125 ks Chandra Complete

- Major post core crossing merger
  - North and south cores plus debris
  - X-ray cores fully disrupted
  - X-ray peak has no major galaxy concentration
- Northwestern interloping merger

Owers et al. 2011
Figure 2. Abell 2744 (z=0.308) 125 ks Chandra Complete

Jellyfish galaxies with induced star formation from high pressure environment

Owers et al. 2012
Abell 2744 - Jellyfish galaxies (Owers et al. 2012)
A "TWIN" TO A2744?

G018.53-25.72 from the Chandra - Planck sample
ABELL 370 (Z=0.375) 95 KS CHANDRA

- A Frontier cluster for HST cycle 3
- Two primary BCGs
- N-S Orientation

- Studied by Bautz et al. (2000)
  - Studied triaxiality
  - Detected submm galaxies
ABELL 370 - TWO LENSED SUBMM GALAXIES

M. Bautz+ 2000

A370 (0.5-5.0 keV; obsid 515)

CX1
z=1.06
Magnification ~ 2.5 (Kneib+93, Ivison+98, Soucail+99)
L_x (observed) > 10^{43} \text{ erg/sec}
Hard X-ray spectra — \ n_H > 2 \times 10^{23} \text{ cm}^{-2}

CX2
z=2.81
L_x (unabsorbed) > 10^{44} \text{ erg/sec}
AGN emission — not starburst

CX1
5” radius circles
CX2
5” radius circles
Summary and the Future

- Chandra and JVLA observations underway
- New insights for cluster mergers and Frontier field structures
  - Talks by Andrade-Santos on MACSJ0717 and Ogrean on MACSJ0416
- Just beginning study of lensed radio and X-ray galaxies (e.g. MACSJ0717
  - Primarily modest magnifications (1-3)
  - Two magnification > 7 X-ray/radio sources
  - Radio emission usually consistent with SFR~10-20 $M_{\text{sun}}$/yr (also few AGN)
- Multi-wavelength comparisons/analyses will provide the greatest insights
  - Combine X-ray/radio/optical
  - Study faint populations, as well as high redshift, starbursts and AGN
  - Resolve X-ray sources, if from star formation and sufficient magnification
Advances in X-ray and optical telescopes

First imaging solar X-ray telescope about the same diameter as Galileo’s 1610 telescope. 380 years after Galileo, Hubble is 100 million times more sensitive.

In ~40 years X-ray telescopes have comparable increase in sensitivity with launch of Chandra.

At 15 years, Chandra is operating very well.
ATHENA APPROVED BY ESA FOR 2020'S
SMART-X UNDER STUDY FOR THE 2020'S

SMART-X team at SAO, PSU, MIT, GSFC, MSFC, JHU, Stanford, Waterloo, Rutgers, NIST, Dartmouth

• 3 m aperture with high angular resolution
  - 30 x Chandra \( (A_{\text{eff}} = 2.3 \text{ m}^2 \text{ at } 1 \text{ keV}) \)
  - sub-arcsec imaging in the inner 8' (diameter) FOV
  - Piezo-electric material on back of thin glass shells shapes figure
  - Useful FOV \~ 20' (diameter); 4'' imaging at the edges

• Science Instruments:
  - 5×5' microcalorimeter with 1'' pixels \( \text{(XMIS)} \)
  - 22×22' CMOS imager with 0.33'' pixels \( \text{(APSI)} \)
  - insertable gratings with \( R = 5000 \) \( \text{(CATGS)} \)

see Vikhlinin et al. 2011 “High Resolution, High Throughput X-Ray Observatory with Adjustable Optics”
M87's youth - Growth of galaxy groups and $10^9 M_\odot$ black holes from $z \approx 6$ to the present

Sloan quasar at $z=6$

“nursing home” at $z=0$

M87, Chandra, 1” pixels

✓ Sensitivity + angular resolution — detect and resolve quasar host halos and galaxy groups at $z=6$

✓ High-res spectroscopy on 1” scales — feedback and physics in clusters, galaxies, SNRs

(MDM simulation by Springel et al.)
THANKS