A Multiwavelength View of the HST Frontier Cluster MACS J0416.1-2403

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Hubble’s Bucket List

Frontier Fields
PUSHING THE LIMITS OF THE HUBBLE SPACE TELESCOPE
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Frontier Fields
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MACSJ0717  MACSJ1149  MACSJ0416  Abell 2744
AGN  Radio Relic  Radio Halo
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Frontier Fields
PUSHING THE LIMITS OF THE HUBBLE SPACE TELESCOPE

MACSJ0717
MACSJ1149
MACSJ0416
Abell 2744

AGN
Radio Relic
Radio Halo
Total mass within a radius of 950 kpc:

\[ \sim 1 \times 10^{15} M_{\odot} \]

- S1
  - \( M \sim 4 \times 10^{13} M_{\odot} \)
- S2
  - \( M \sim 1 \times 10^{13} M_{\odot} \)

\( \approx 200 \text{ kpc} \)

Jauzac et al. (2014)
SCENARIO 1

A pre-merger system:
C2 approaches C1 for the first time.

SCENARIO 2

A post-merger system:
C2 approaches C1 for the second time.

Jauzac et al. (2014)
0.5 - 3 keV Chandra surface brightness map, based on 180 ks of data (PIs: Murray, Jones).
$z = 0.40$
$T = 9.6 - 10.3$ keV

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Is C1 a cool core?
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Peaked central brightness BUT...

High ellipticity

600 kpc
Peaked central brightness BUT...

- High ellipticity
- Deviations from symmetry

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- Deviations from symmetry
- Hot, high-entropy core

$T \approx 13 \text{ keV}$
$n \approx 5 \times 10^{-3} \text{ cm}^{-3}$

Sanderson et al. (2009)
Peaked central brightness BUT...

- High ellipticity
- Deviations from symmetry
- Hot, high-entropy core

600 kpc
Peaked central brightness BUT...

- High ellipticity
- Deviations from symmetry
- Hot, high-entropy core

\[ \chi \]

\[ \text{DOUBLE } \beta\text{-model} \]
Peaked central brightness BUT...

- High ellipticity
- Deviations from symmetry
- Hot, high-entropy core
- Evidence of a 2nd subcluster

DOUBLE $\beta$-model
The ratio:
\[ R_S = \frac{S_{0,1}}{S_{0,2}} \]
is closest to 1 in the direction of the "hidden" subcluster.
C1 is undergoing a merger with a less massive cluster not immediately visible in the X-ray map.
Is C2 a relaxed cluster?
\[ \beta = 0.6 \text{ (fixed)} \]

\[ r_c = 150 \pm 5 \text{ kpc} \]
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\[ \beta = 1.6 \pm 0.3 \text{ (free)} \]

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\( r_c = 460 \pm 70 \text{ kpc} \)
C2 is also undergoing a merger with a smaller cluster not immediately visible in the X-ray map.
Provisional Summary

C1 is merging
- strongly elongated
- hot core
- high central entropy
- ICM substructure
- C1 = multiple subclusters

C2 is merging
- flat X-ray brightness
- poor/unphysical $\beta$-model fit
- density discontinuity in the ICM
Are C1 and C2 interacting with each other?
- no clear evidence of typical merger shocks
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• no large dissociation between the DM and the gas components (Jauzac et al. 2014)

C1 and C2 have not yet merged with each other
Summary

• The HST Frontier cluster MACS J0416.1-2403 is a hot (T ~ 10 keV), massive (M ~ 1e15 M\textsubscript{\odot}) merging cluster.

• The main subclusters are interacting with less massive galaxy groups, as evidenced by substructure and weak density discontinuities in the ICM.

• However, no clear evidence of interaction between the two main subclusters.

• **Likely scenario:** MACS J0416.1-2403 is a place of active cosmic structure growth. We are witnessing a pre-merging system.
**Fig. 2:** Zoom-in on the N cluster core. A “cavity”-like feature is seen NW of the core.
Calculate the local sky background surface brightness from the outer bins of the profile.

Keeping the sky background fixed to its best-fitting value, fit the inner part of the profile.

Subtract the stowed background profile from the surface brightness profile across the "cavity".

Bin the net profile to have at least 1 count/bin.

Use Cash statistics for the fits, rather than chi-squared statistics.

Fit various underlying density models to the data, assuming that the plasma is isothermal.

Fig. 2: Zoom-in on the N cluster core. A "cavity"-like feature is seen NW of the core.
Calculate the local sky background surface brightness from the outer bins of the profile.

Keeping the sky background fixed to its best-fitting value, fit the inner part of the profile.

\[\chi^2\]

**Fig. 2:** Zoom-in on the N cluster core. A “cavity”-like feature is seen NW of the core.

\[\beta\text{-model}\]

\[\text{double } \beta\text{-model}\]

\[c = 99.999\%\]

[Graphs showing surface brightness profiles and fits with chi-squared values and parameters.]
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Spectroscopic Analysis

From the total spectrum of a partial annulus, subtract the stowed background spectrum from the same region.

Bin the spectra to have at least 1 count/bin.

Use Cash statistics for the fits, rather than chi-squared statistics.

Keeping the sky background model fixed, fit the net source spectra with single-temperature APEC models.

Fig. 2: Zoom-in on the N cluster core. A “cavity”-like feature is seen NW of the core.
Model the local sky background.

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**Fig. 2:** Zoom-in on the N cluster core. A “cavity”-like feature is seen NW of the core.

**Fig. 3:** Temperature profile across the NW “cavity.”

1 arcsec = 5.340 kpc

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