Reconstructing galaxy cluster mergers
with multi-wavelength observations and
hydrodynamical simulations

The case of Abell 2146

Urmila Chadayammuri
Yale University/Chandra X-ray Center Pre-Doctoral Program

with
Paul Nulsen, John ZuHone, Felipe Santos, Daisuke Nagai, Lindsay King, Miyoung Choi, Helen Russell
Abell 2146

- Detected as a merging cluster in the X-ray by Russell+ 2010
- Recently completed 2Ms XVP observations (PI Russell, in prep.)
- deepest yet of merging galaxy cluster
Long-Term Questions

• What is the nature of microphysics of the ICM?
  • electron-ion equilibration, thermal conduction and viscosity

• Why is extended radio emission suppressed?
  • Lack of “fossil electrons” from previous mergers/AGN events that could be re-accelerated?
Immediate Challenge

Rapidly narrow down space of cluster merger parameters using hydrodynamical simulations and constraints from multiple observations.
GAMER-2

- **GPU-accelerated Adaptive M**E**sh** R**efinement code**
- 100x faster than FLASH, 10x than Enzo
- Available modules:
  - ✓ non-radiative gas with self-gravity
  - ✓ star formation and feedback
  - ✓ radiative cooling
  - □ MHD

Schive+ 2017
Step 1: Initial Conditions

- Halo masses $M_1, M_2$ from lensing and dynamical analyses
- Truncated NFW profile for the dark matter - $c_{DM}$
- Vikhlinin modified beta profile for the gas - $\alpha_{gas}$
- Initial velocity $v_{rel}$
- Impact parameter $b$

8 free parameters
Step 2: Separation of BCGs

- BCG positions limited only by astrometry, trace $\phi_{\text{grav}}$
- Slice of gravitational potential in plane of the merger

➤ identify local minima
Result: 1-3 snapshots

- Lucky because visibility of shock fronts + dynamics tightly constrains projection angle. If $\theta_{proj}$ less certain, more snapshots.

- But strong selection because BCGs move very fast close to merger!
Step 3: Rotate and project

- Sets rotation in plane of sky
- Then vary projection angle $\pm 20^\circ$

$M_1 = 9 \times 10^{14} M_\odot, M_2 = 2.4 \times 10^{14} M_\odot$

$b = 50 \text{ kpc}, t = 0.3 \text{ Gyr post periapsis}
Step 4: Feature recognition

- Identify bright, high contrast regions

**Canny algorithm** - vary smoothing length, minimum contrast

![Canny algorithm examples](image-url)
Step 5: Feature sorting

- Sort adjacent points into separate features
- Apply surface brightness/contrast cuts from X-ray maps
  - feature lengths, relative separations
  - T, profiles across them

Features from T map
Step 6: Fit arcs

- For mergers, the shock fronts are more circular, whereas disrupted cool cores are more irregular.
Key feature observables

- Radius of curvature + standoff distance
- Highly sensitive to halo masses, initial velocities, impact parameter
- Gas parameter effects much smaller scale - useless to fine-tune without better physics
To be continued

- MHD
- viscosity (isotropic + Braginskii)
- thermal conduction
- electron-ion equilibration through Coulomb collisions
Conclusions

• We present a pipeline to compare simulations to multi-wavelength observations to constrain cluster merger parameters

• Current case: Abell 2146

1. Initial conditions from **lensing + dynamical analyses**

2. **Positions of BCGs**/potential minima strongly constrain time in simulation

3. Fix rotation angle in plane of sky

4. **X-ray emissivity, temperature maps** then relatively rank images
   - edge-finding algorithms allow **shock/cold front detection**
   - Then compare radius of curvature, standoff distance

5. Iteratively explore parameter space with fast simulation codes like GAMER
Backups
Parameter tests: Impact parameter

b = 100                      b = 250                      b = 375

Chandra 0.3-7.0 keV

- Upstream shock
- Subcluster core
- A2146-A
- Bow shock
- Plume

1 arcmin = 222 kpc
Parameter tests: Halo mass

Lensing models degenerate between concentration and total mass

Greater halo mass $\rightarrow$ larger features, greater separation between bow shock and cold front

$M_1 = 1.1 \times 10^{15} \, M_{\text{sun}}$

$M_1 = 8.1 \times 10^{14} \, M_{\text{sun}}$
Parameter tests: halo concentrations

c_{DM} of main halo

α of main halo

c_{DM} of secondary halo