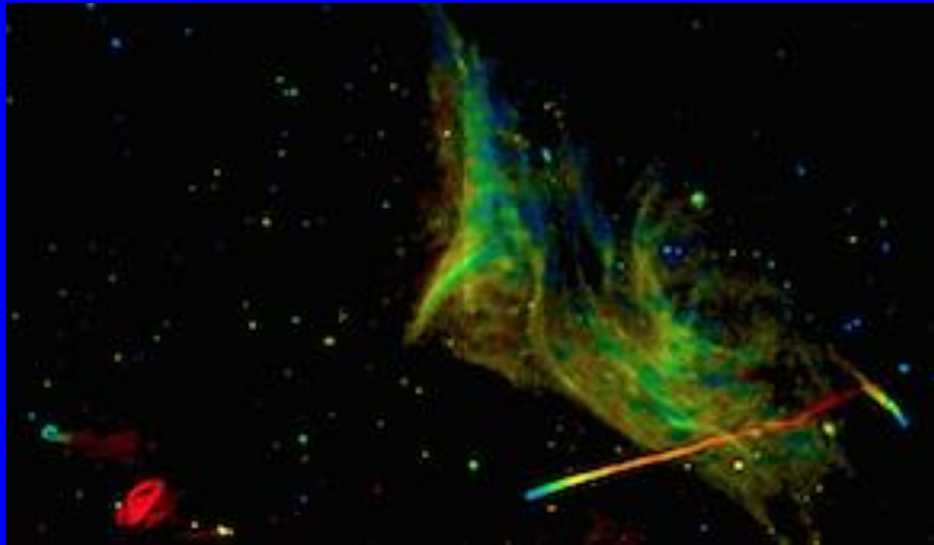


Diffuse Synchrotron Emission in Clusters of Galaxies - What's Next?



Summary Talk

Craig Sarazin

University of Virginia

Opening Talk – Observations of radio halos, mini-halos and relics

Observations of radio halos, mini-halos and relics – review - **Tiziana Venturi**

- Nice overview: properties of halos, relics, mini-halos
- A few cool core clusters with halos? Minor mergers? Large sloshing?
- Mini-halos: Cool cores, sloshing cold fronts correlation Association BCG radio galaxies? Source of electrons?
- Relics: single vs. double? Always with shocks? Problems with direct shock acceleration?
- Long radio tails: origin?

Radio Observations

Early results from SKA pathfinder – **Melanie Johnston-Hollitt**

- Discovering odd things, not fit into halo, relic classes.
Need new system
- Need to push surveys, scaling relations to lower L_x , M

Observations of radio relics – **Reinout Van Weeren**

- Toothbrush: Shock can't power radio relic with thermal injection
- Evidence of re-acceleration: relics \rightarrow AGN tails
 - A3411-3412, MACS0717

LOFAR Observations

LOFAR observations of clusters of galaxies -

Tim Shimwell

- Toothbrush, A2256,
- Large FOV -> great for surveys LoTSS.
- Shocks: A655 no relic, halo extends out to it.

Exploring the diffuse emission from clusters of galaxies with MSSS – **Emanuela Orru**

- MSSS = Multifrequency Snapshot Sky Survey
- Short observations, but shows power of LOFAR

LOFAR Observations

LOFAR view of the Sausage cluster – Duy Hoang

- Mach numbers from radio spectra at shock agree with X-ray values => radio aging model too simple
- But, does the X-ray show a shock at the edge of relic?

LOFAR discovery of a double radio halo in Abell 1758 – Andrea Botteon

- Double cluster, N & S. Double radio halo as well. S cluster low mass for having a halo. May have a relic.
- Bridge of emission connecting N & S, high X-ray entropy

Gamma-ray Observations

High-energy observations of clusters – review -
Gamma-ray observations - **Stephan Zimmer**

- Nine years of Fermi – no clear detections (only AGNs),
 $P_{\text{CR}} / P_{\text{gas}} < 1 \%$
- Virgo, Coma – no clear diffuse emission
- Compton Telescopes: no detection

Discussion – Radio Observations

Marcus Brüggen

- Classify (Melanie) or not classify (Larry)? Melamie will make a Wiki
- Lack of *high frequency* data in some cases. Need curvature not just one spectral index?

Theory and Simulation

Cosmological simulations of clusters – Review - Christoph Pfrommer

- Weak shocks not good at accelerating cosmic rays.
Re-acceleration wins Mach < 4
- $P_{\text{CR}}/P_{\text{gas}}$ significant only at large radii
- Curved shocks generate vorticity, turbulence
- Cosmological simulations -> hard to get correct seed populations

Theory & Simulations

Properties of Merger-Driven Shocks in Galaxy Clusters – Dongsu Ryu

- Simulations: Shocks in simulations have complex geometry, non-uniform
- Shock energy greatest ~ 1 Gyr after merger, $r \sim 1.5$ Mpc

A Lagrangian view on the gamma-ray and diffuse radio emission in galaxy clusters - Denis Wittor

- Relic X-ray vs. radio Mach \rightarrow due to radio weighting higher Mach number along LOS

Theory & Simulations

Simulations of the Sausage Cluster - **Julius Donnert**

- Idealized cluster merger simulation, CC & nonCC clusters
- Infall velocity too large

Theory and Simulation

Origin of magnetic fields in clusters - **Marcus Brüggen**

- Initial fields: due to AGN (in high densities) or primordial (uniform)?
- ICM: turbulent dynamo, filaments less = a test
- Turbulence: 4% of energy -> B field

Magnetic Fields

Observations of magnetic fields in clusters -

Federica Govoni

- Faraday rotation` measurements, combined with simulations of clusters with radio galaxies
- Abell 194: scale length = 64 kpc, $B = 1.5 \mu\text{G}$
- No clear correlation of B with kT (mass)

Magnetic fields measurements in clusters -

Valentina Vacca

- Algorithm for determining LSS B from RM catalog
- RM catalog of 4×10^4 sources, but only 4000 have z

Magnetic Fields

Magnetic Fields Properties Derived from Radio Relics - Matthias Hoeft

- Toothbrush models: Projection very important
- Electrons lose energy rapidly
- Filaments due to feature in projection on shock surface, not within shock

Magnetic Fields

Deep JVLA observations of the Toothbrush galaxy - **Kamlesh Rajpurohit**

- Beautiful high resolution observations of spectral index and RM variation of relic and halo
- Fine filaments

Cluster magnetic fields: the rest of the story - **Larry Rudnick**

- Hard to separate intrinsic AGN and cluster RM
 - Fractional polarization increases with source size
 - AGN have intrinsic RM
- Future: Radio Galaxy Zoo, POSSUM, VLASS

Low Frequency Radio

Galaxy clusters at ultra low-frequencies -

Francesco De Gasperin

- Abell 1033: remarkable new filamentary source, $\alpha < -4$, due to turbulence in tail?
- LoL-ss survey, 42-66 MHz, dead radio galaxies

Deep in the (Un)known: the Sausage Cluster –

Gabriella Gennaro

- JVLA: Lots of new features, new relics
 - N relic breaks up into filaments
 - S relic with AGN tail -> re-acceleration?

Magnetic Fields & Polarization Discussion

Introductory Talk On Magnetic Fields &
Polarization – Observation - **Annalisa Bonafede**

- RM \rightarrow B, complicated modeling required

Introductory Talk On Magnetic Fields &
Polarization – Theory – **Dongsu Ryu**

- If fields are due to turbulent dynamo, why are relics highly polarized in uniform direction?

Magnetic Fields & Polarization Discussion

- Can polarization of relics be explained by shock compression?
- How can we test assumptions in RM analysis? If not, how do they affect the cluster field? Always lower it?
- Relative role of plasma micro-physics and large scale hydro in B field?

X-rays

Observations of Galaxy Clusters in X-Rays – review

- Maxim Markevitch

- Hitomi Perseus: gas turbulence
- S, Ca, Fe charge exchange lines probably seen
- Chandra A520: Electrons heated at shock
- “Channel” depressions in X-ray
- No shock at Sausage relic, bump due to IC emission?

X-Ray Observations of Cluster (~~Shocks~~) Radio

Relics – Hiroki Akamatsu

- A2256 – two shocks, no radio emission? Now seen
- New LOFAR data: better agreement M_{radio} vs. M_X

SZ

SZ Observations of Cluster Shocks – Kaustuv Basu

- SZ from shock affects radio synch. at 10 GHz
- ALMA: Gordo shock , Bullet: preliminary result shock

Low Frequency Radio

Cluster Population Studies - **Rossella Cassano**

- Fraction of halos lower than merger fraction
- LOFAR, SKA precursors: will find lots of halos in low mass clusters, high z clusters

Study of Non-Merging Massive Clusters at Low Frequency – **Federica Savin**

- Mini halos in relaxed clusters
- RXJ1720, mini-halo, and tail in center
- Intermediate in size, mini-halo to halo

Low Frequency Radio

Ultra-Steep Spectrum Radio Relics in Clusters - Tracy Clarke (Simona Giacintucci)

- VLSS: sample of steep spectrum sources
- A2443: complex, 3 tails from BCGs, relic with X-ray shock
- Many other interesting sources

Ultra Steep Spectrum Sources in Galaxy Clusters - Soumyajit Mandal

- GMRT 1450 MHz survey, TGSS, looked at clusters
- Fossil radio plasma, compressed by shocks
- Very complex, example: A1914

Particle Acceleration - Theory

Particle acceleration in clusters - review - Tom Jones

- Nice models!
- Separate “injection” problem from DSA
- AGN/shock interaction may be important
- Role of turbulence

Cosmic Ray Acceleration in Clusters Updated – Walter Jaffe

- Particles diffuse ahead of shock – visible in radio?
- No relics in “pre-mergers”, as clusters start to merge

Particle Acceleration in Shocks

Particle Acceleration in Collisionless Shocks – Anatoly Spitkovsky

- PIC simulations – nice movies!
- Proton acceleration requires B parallel (<50°)
- Electrons probably accelerated for all angle

Electron Heating and Acceleration at Quasi-Perpendicular Shocks – Lorenzo Sironi

- PIC simulations of perpendicular shock
- $T_e / T_{ad} = 0.1 (M_s - 1) + 1$, lower limit for parallel
- Effective electron injection, shock drift acceleration

Particle Acceleration in Shocks



Don't electrons ever get dizzy?

Particle Acceleration in Clusters

Diffusive Shock Acceleration Model With Postshock Turbulence For Radio Relics - Hyesung Kang

- Problem with re-acceleration – uniform spectral index?
- Postshock turbulent acceleration works
- Shock beyond fossil cloud in Sausage?

Cosmic Ray Transport in Galaxy Clusters – Peng Oh

- Seed electrons secondaries from protons, need to spread
- Protons can move super-Alfvénic, give flat distribution

Wednesday Discussion

Julius Donnert

- Does Coma spectrum really steepen?

Cool Cores, Mini-Halos, Feedback

Cool-Core Clusters: Thermal - Non-Thermal Connection - **Simona Giacintucci**

- Mini halos in cool cores, turbulent acceleration due to core sloshing
- Ophioc. Cluster: giant bubble with $\alpha = -3.45$!!

Radio Mode Feedback: Theory and Simulations - **Manel Perucho**

- 2D and 3D models of jets in clusters
- Main energy deposition is due to shocks

Cool Cores, Mini-Halos, Feedback

Cosmic-Ray Heating and Mini-Halos - **Svenja Jacob**

- Steady-state models
- Self-regulated feedback cycle due to CRs?
- Higher star formation in clusters with mini-halos?

Radio Halos

Statistical Study of Radio Halos in a Mass-Selected Sample of Galaxy Clusters - Virginia Cuciti

- Largest mass selected (from Planck) sample
- New halos and relics, A1451, Z0634, faint and small
- Z0634: relic at a very large radius, re-energized AGN?

Results from a Radio Halo Search in High-Mass SZE Selected Clusters – Martin Sommer

- Occurrence of radio halos? Time scale of halo in merger
- JVLA of 26 Planck clusters, 23 found with halos
- Halos in cool/warm core clusters

Radio Observations

State-of-the-Art JVLA Observations of Clusters of Galaxies: Revealing New Physics about the Non-Thermal Particles - **Julie Hlavacek-Larrondo**

- JVLA 230-470 MHz image Perseus, lots of structures, correlated with X-ray
- A2146: 2 shocks, detected radio relic and relic/halo

X-rays and Nonthermal Energy

Inverse-Compton Hard X-Ray Emission from Clusters: NuSTAR – Daniel Wik

- Inverse Compton? Only upper limits in Coma, Bullet, AS753, A2163, Oph.
- Hard emission from shocks – not yet constraining
- Stray light problem

X-rays and Nonthermal Energy

Indirect Turbulence Measurements in Galaxy Clusters with Hitomi and Chandra – Irina Zhuravleva

- Resonance line scattering, Hitomi, Perseus, $v = 150$ km/s, same as line width
- Surface brightness fluctuations, Coma, $v = 100$ - 150 km/s for $l = 10$ - 30 kpc, similar results other CC clusters

X-rays

X-Ray Study of the Merging Double-Radio-Relic Cluster Abell 3376 with Suzaku - **Igone Urdampilleta**

- High speed merger, two outer relics, shock at western relic
- Eastern relic, complex radio structure, shock displaced from outermost radio edge

A Combined JVLA and Chandra Study of the “Kite” Radio Source in Abell 2626 – **Alessandro Ignesti**

- Diamond-shaped radio source & mini-halo
- Arcs not due to jet procession?
- Associated with cold fronts, due to turbulent acceleration due to sloshing?

LOFAR

The Corona Borealis Supercluster Seen with LOFAR – Alexander Drabent

- Abell 2061: central radio halo has small USS source embedded in center
- A2069a: USS halo, A2069b: mini-halo?

Theory vs. Observation Discussion

Toy Models vs. Toy Observers



Theory vs. Observation Discussion

Introductory Talk– Understanding and Problems - Gianfranco Brunetti

- Relativistic electrons: how to keep electrons around
- Could AGNs contribute particles?
- Where are the gamma-rays?
- Do we understand bimodality?
- Do we understand turbulent acceleration (no)?

Relativistic Electrons

An ABC Estimate of the CR Electron Content in Galaxy Clusters through Radio Relics - **Jakob Gelszinnis**

- ABC = Approximate Bayesian Computation
- MUSIC-2 numerical simulations of clusters

On the Connection between Turbulent Motions and Particle Acceleration in Galaxy Clusters – **Stefan Zimmer for Dominique Eckert**

- Density fluctuations (X-ray) vs. radio halo or not
- Bimodal: radio halos are turbulent, $P_{\text{radio}} \sim \sigma_V^3$

Star Formation and AGNs

Merging Clusters and Star-Formation – Andra Stroe

- Toothbrush and Sausage clusters
- Merging clusters today vs. protoclusters, field
- Merger shock-induced star formation

FR-Type Radio Sources in Cosmos: Relation to the Large-Scale Environment – Eleni Vardoulaki

- FR types vs. environment
- FR I at edge of X-ray groups, FR II's more disturbed in groups
- No dependence on large scale environment

Star Formation and AGNs

Cosmic Radio Background and its Discovery Potential – Tessa Vernstrom

- Diffuse background, halos, etc.
- Measure from confusion diffuse emission
- Cross-correlate with galaxy density

Dark Matter & Lensing

Dark Matter in Clusters and Radio Observations – Emma Storm

- Use radio to search for dark matter annihilation products in clusters.
- Future with LOFAR, ASKAP, and APERTIF

A Weak-Lensing Analysis of the Synchrotron Rich, Double Radio Relic Galaxy Cluster, P1ck G287.0+32.9 – Kyle Finner

- Massive cluster with 2 highly asymmetric radio relics
- Mass = Main cluster + 3 subclusters
- 2 subcluster make radio relics

Musings

- ❖ Bright future: LOFAR hitting its stride, SKA precursors, etc.
- ❖ How will we disentangle the complex radio structures now being discovered?
- ❖ Seed particles for halos and relics:
 - ❖ Source? AGNs? LSS shocks? Secondaries from CR protons?
 - ❖ Properties? Can low frequency radio observations give us information?

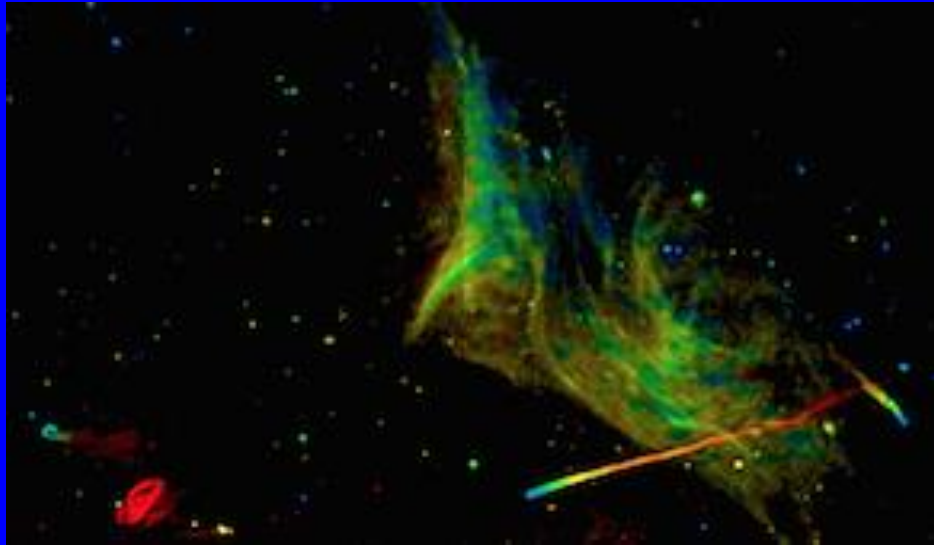
Musings – Cont.

- ❖ Radio Mini-Halos
 - ❖ Source of electrons, acceleration mechanism?
 - ❖ Tied to central AGNs?
 - ❖ Tied to sloshing cold fronts?

Musings – Cont.

- ❖ Radio Mini-Halos
 - ❖ Source of electrons, acceleration mechanism?
 - ❖ Tied to central AGNs?
 - ❖ Tied to sloshing cold fronts?
- ❖ Are we running out of cute names for clusters and relics?
 - ❖ Need an IAU Commission to select?

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Thanks so much to the local organizers!



Fabio



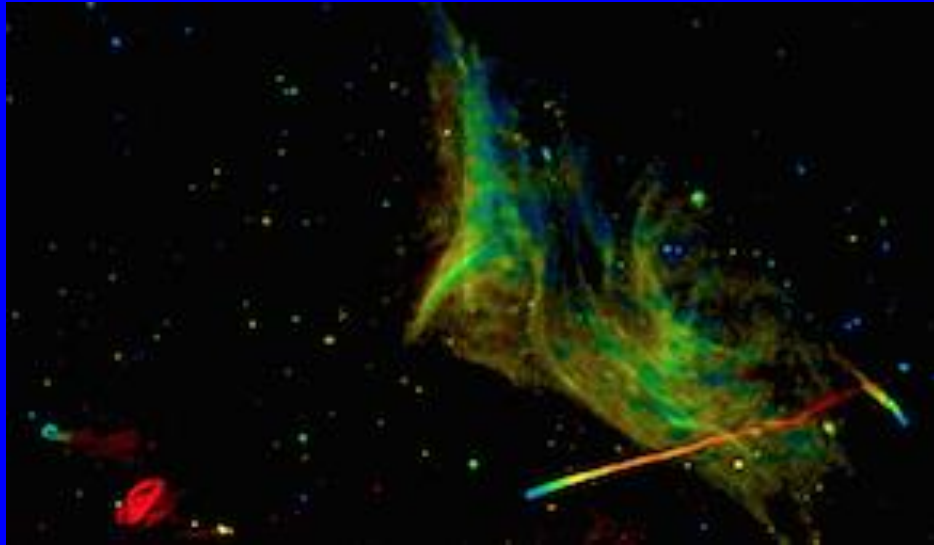
Huub



Alexandra

And many others!

Diffuse Synchrotron Emission in Clusters of Galaxies - What's Next?



This was an extremely productive, useful, and fun meeting!

I will leave here fully “en-Leiden-ed”!!

Spell
check
error?