A Long Wavelength View of Cosmic Rays
Cosmic Rays in the Context of Multimessenger Astronomy
Joseph Lazio
A Long Wavelength View of Cosmic Rays

• What’s radio astronomy got to do with it?!?
• Neutrino-emitting blazars?
• Intergalactic magnetic field and the cosmic web
• Cosmic structure formation and particle acceleration
Radio Astronomy?

Frequency $\nu \sim 10$ GHz

$E_\nu = h\nu \sim 40 \, \mu eV$
Radio Astronomy?

Frequency $\nu \sim 10$ GHz

$E_{\nu} = h\nu \sim 40 \mu$eV

Synchrotron-emitting electron emits most radiation at

$\nu_c \sim \gamma^2 \nu_g = 2.8$ MHz $\gamma^2 (B/1 \text{ G})$

Non-relativistic gyrofrequency

$\nu_g = eB/(2\pi m_e)$
Radio Astronomy?

Frequency $\nu \sim 10$ GHz

$E_\nu = h\nu \sim 40$ $\mu$eV

- $E_e \sim 30$ GeV or
- $\gamma \sim 60,000$
- $B \sim 1$ $\mu$G

Radio-wavelength photons may be low energy, but the emitting electrons are high energy

Synchrotron-emitting electron emits most radiation at

$\nu_c \sim \gamma^2 \nu_g = 2.8$ MHz $\gamma^2 (B/1\ G)$

Non-relativistic gyrofrequency

$\nu_g = eB/(2\pi m_e)$
A Long Wavelength View of Cosmic Rays

• What’s radio astronomy got to do with it?!?
  ➢ Radio photons typically produced by cosmic ray electrons
• Neutrino-emitting blazars?
• Intergalactic magnetic field and the cosmic web
• Cosmic structure formation and particle acceleration
Neutrino-Emitting Blazars?

2017 September 22, IceCube detects 24 TeV $\nu_\mu$

- Track of $\nu_\mu$ pointed to TXS 0506+056
  - TXS 0506+056 identified in Texas 365 MHz survey (Douglas et al. 1996)
  - What is a “blazar”? Radio source with jet pointed toward observer, significant variability
Neutrino-Emitting Blazars and Radio Astronomy

I. Modest-sized radio telescopes can provide long light curves for characterizing source behavior

- Owens Valley Radio Observatory 40 m @ 15 GHz
- Metsähovi Radio Observatory 14 m @ 22 GHz and 37 GHz
- Univ. Michigan Radio Astronomy Observatory 26 m @ 4.8 GHz, 8 GHz, 14.5 GHz
- GAVRT 34 m @ 8 GHz?

IceCube Collaboration et al.
I. Modest-sized radio telescopes can provide long light curves for characterizing source behavior

II. Sub-parsec resolution obtained, enabling tests of models for neutrino (and cosmic ray) generation

- Single vs. multiple zones?
- Leptonic or hadronic?
Neutrino-Emitting Blazars and Radio Astronomy

Coming Attraction?

I. Modest-sized radio telescopes can provide long light curves for characterizing source behavior

II. Sub-parsec resolution obtained, enabling tests of models for neutrino (and cosmic ray) generation
   - Single vs. multiple zones?
   - Leptonic or hadronic?
     ➢ Circularly polarized jets could indicate leptonic jet ($e^{-}$-$e^{+}$)

Radio Astronomical Studies
Neutrino-Emitting Blazars and Radio Astronomy

The Future

• Powerful complement of (VLBI-relevant) facilities available or in development
  – Very Long Baseline Array (VLBA)
  – European Very Long Baseline Interferometry Network (EVN)
  – Australian Long Baseline Array (LBA)
  – Atacama Large Millimeter/submillimeter Array (ALMA)
  – Event Horizon Telescope (EHT)
  – East Asian Very Long Baseline Interferometry Network (EAVN)
  – Next-generation Very Large Array (ngVLA) – design & development
  – Square Kilometre Array Phase 1 (SKA1-Mid) – construction initiated

• Monitoring programs quite feasible
  ➢ Too often perceived as “not novel” 😅
Fast Radio Bursts (FRBs) and Neutrinos?

- Fast radio bursts (FRBs) = intense millisecond duration decimeter-wavelength bursts (~ 1 Jy ms @ 1 GHz) of extraterrestrial origin … and FRB 200428/SGR 1935+2154
- High brightness temperature (> $10^{32}$ K) → extreme conditions of emitter
  - Strong magnetic fields, ultra-relativistic shocks, …
  - No definitive counterparts … yet?
What’s radio astronomy got to do with it?!?
- Radio photons typically produced by cosmic ray electrons
- Neutrino-emitting blazars? (and FRBs?)
- Intergalactic magnetic field and the cosmic web
- *Cosmic structure formation and particle acceleration*
Most baryons likely in “cosmic web” --- Mpc-scale filaments connecting clusters of galaxies

➢ If magnetized, scatter or “steer” ultra-high energy CRs (UHECRs)?
Two views of local cosmic web --- toward Virgo Cluster

• If magnetized, scatter or “steer” ultra-high energy CRs (UHECRs)?
• M87 often considered local accelerator

P.S. Right Ascension is supposed to be in sexagesimal notation (HH:MM)
Radio Bridges and the Cosmic Web

- Multi--Mpc-scale “radio bridges” being found between merging clusters of galaxies
- Synchrotron emission
  - What’s the acceleration mechanism?!?
  - Magnetic fields clearly present

A399-A401 (Govoni et al.)
Consider pairs of luminous red galaxies (LRG)---trace cosmic overdensities

1. Stack them;
2. Subtract point source model; …

➢ Find excess synchrotron radio emission
➢ Find excess hot gas

(Vernstrom et al.)
Consider pairs of luminous red galaxies (LRG)---trace cosmic overdensities

1. Stack them;
2. Subtract point source model; …

➢ Find excess synchrotron radio emission
➢ Find excess hot gas

(Vernstrom et al.)
Intergalactic Magnetic Field and the Cosmic Web

Future

Some current and emerging facilities

➢ Need high surface brightness to detect diffuse cosmic web
➢ Need (very) long wavelengths to detect low-energy CR electrons (because acceleration is not efficient within cosmic web? or CR electrons have diffused significantly from site of acceleration?)

• Australian SKA Pathfinder
• SKA1-Mid(?)
• LOFAR
• Future space-based telescope?

Credit: ATNF; SKAO; ASTRON
A Long Wavelength View of Cosmic Rays

Summary

• **What’s radio astronomy got to do with it?!?**
  - Radio photons typically produced by cosmic ray electrons

• **Neutrino-emitting blazars? (and FRBs?)**
  - Radio-wavelength observations have been key to identifying potential neutrino-emitting sources
  - Powerful probe of where jet is being launched, potentially neutrinos being produced

• **Intergalactic magnetic field (IGMF) and the cosmic web**
  - Structure of IGMF will affect (UHR)CR propagation
  - Radio-wavelength observations revealing aspects of IGMF, both locally and cosmologically

• **Cosmic structure formation and particle acceleration**
Position angle of linearly-polarized radiation rotates as it traverses magnetized region

- Rotation angle $\chi = \int n_e \vec{B} \cdot d\vec{l}$
- Formally: different propagation speeds for Ordinary and eXtraordinary modes
Two clusters ($M \sim 10^{14} M_\odot$) fall towards each other …

- Collide with speeds $> 1000 \text{ km/s}$
- Merge on time scale $\sim 1 \text{ Gyr}$

Ricker & Sarazin 2001

As two clusters pass through each other, significant energy ($\sim 10^{63} \text{ ergs}$) injected into intracluster medium (ICM)

- large-scale bulk disturbances,
- fast-travelling shocks, and
- cluster-wide turbulence

Stroe et al. 2020

Fantastic site for particle acceleration!
Maximum energy of accelerated particle depends on
- charge (q);
- magnetic field strength (B);
and
- size of accelerating region

Intercluster or intergalactic medium is fantastic site for (ultra-)high energy CR acceleration!
Correct? Maybe?
Cosmic Structure Formation and Particle Acceleration

- Ample indications of CR electrons, as traced by (long-wavelength) radio emission in (energetic) merging clusters
  
  Also injection from active galactic nuclei jets

- “The first clear detection of high-energy $\gamma$-ray emission from a galaxy cluster will undoubtedly constrain the baryonic particle content as well as the uncertainty in the estimates of the magnetic field, and consequently enable vastly improved modeling of galaxy clusters over the entire electromagnetic spectrum.” (Atwood et al., “The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission”)
Cosmic Structure Formation and Particle Acceleration

ZWCL 1447.2+2619

- Merging clusters
- Northeast-southwest orientation
- Simulations guided by weak-lensing mass constraints

Potentially have made first pass, and are just starting to fall together again

Lee et al.

Radio Astronomical Studies

jpl.nasa.gov