The Extragalactic Radio Background
Challenges and Opportunities

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Extragalactic Backgrounds

![Graph showing energy density vs. frequency for different wavelengths: Radio, Microwaves, Infrared, Optical, X-ray, and Gamma-ray. The y-axis is labeled as Energy Density \( E_V \) (nW m\(^{-2}\) sr\(^{-1}\)). The x-axis represents Frequency (Hz).]
Early Background Estimates

\[ T_{\text{ex}} \text{ From Spectral Index Variations} \]
\[ T_{\text{ex}} = 30-80 \text{ K at 176 MHz} \]
\[ = 3-6 \text{ K at 408 MHz} \]

Assumes extragalactic component has different spectral index than galaxy

3D modeling of full-sky surveys
Fit 408 MHz survey:
- Thin disk + thick disk + spiral arms
- Extragalactic component

\[ T_{\text{ex}} = 6 \text{ K at 408 MHz} \]
(assumed value, not fit)
(includes 2.7 K CMB)

Phillips et al 1981
Beuermann et al 1985
Monopole Component of the Radio Sky

Coldest pixels ~ 11 K across much of radio sky
Consistent with isotropic source
Point sources contribute ~ 2—3 K
Where does the rest come from?

408 MHz survey
Stereographic
Monopole Component of the Radio Sky

Coldest pixels $\sim 11$ K across much of radio sky

Consistent with isotropic source
Point sources contribute $\sim 2\text{—}3$ K
Where does the rest come from?

408 MHz survey
Stereographic

Linear scale chosen to highlight isotropic component
Simple Background Estimate

Recall that 408 MHz survey has pixel noise \( \sim 1 \) K

Histogram of coldest patch has
- Peak at 13.6 K
- Gaussian width 0.65 K

Beware of bias: Coldest pixels include downward noise fluctuations

Subtract CMB 2.7 K to get
\[ T_{\text{ex}} \sim 11 \] K
Advent of Precision Data

**Problem**: Surveys from 60's to 80's not intended for background detection
  Calibration errors 5–20%
  Zero level errors of many K
Not a problem for bright structures, but difficult to nail down fainter background

**ARCADE-2 sky measurements**
Compare sky to external calibrator
  • at multiple frequencies
  • using fully cryogenic instrument
  • from a balloon platform
  Gain error < 0.03%
  Zero level error < 10 mK
Monopole component detected in all radio surveys
Not dependent on ARCADE data alone

Question: Where does it come from?
Origins and Issues

Radio Background is ...

Extragalactic

Galactic

Nearby

Polarization
Far-IR corr

Distant

Unique Halo
X-ray limit

Discrete

Source Density
Far-IR corr

Diffuse

Source Amplitude
X-ray limit

Problems
Extragalactic Source Populations

Simplest solution: monopole component as integrated emission from discrete sources

Problem: Required faint populations exceed density of galaxies in Hubble UDF by factor of 100

Condon et al. 2012
Radio/Far-IR Correlation

Independent Check on Extragalactic Origin

Tight correlation between radio and IR emission
Use observed far-IR background to predict integrated radio emission from same galaxies

Predict $T_R \sim 1\text{—}2\text{ K at 408 MHz}$

- Consistent with radio source counts
- Too small to make up observed background

Dwek & Barker 2002, APJ, 575, 7
Franceschini et al 2001

Condon 1992, ARAA, 30, 575
Diffuse Extragalactic Emission

Could monopole be integrated emission from sources of low surface brightness?

**Constraint from radio vs X-ray backgrounds**

Radio emission from ultra-relativistic electrons

\[
N(E) = \kappa_e E^{-p}
\]

\[
I_\nu \sim \kappa_e B^{(p+1)/2} \nu^{-(p-1)/2}
\]

X-ray emission from inverse Compton scattering of CMB photons from **same** electrons

\[
I_\nu \sim \kappa_e \kappa_\gamma f(p)
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Singal et al 2010
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Frequency dependence sets \( p \)

Knobs to set amplitude

CMB sets lower limit

Singal et al 2010
Diffuse Extragalactic Emission

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Large magnetic field B required to avoid over-producing X-rays

\[ B > 1 \ \mu G \]

Conflicts with B < 0.2 \ \mu G for IGM

Singal et al 2010
Galactic Halo

Model radio sky as disk + halo + anisotropic pieces
Halo diameter 28 kpc extends beyond solar circle
Explains why coldest patches are not at poles

Problem ...
Implies detectable halo
Not seen in survey of edge-on spirals
Where Are The Radio Halos?

Radio Properties of Typical Spirals
- Little or no extended emission
- Few cases of isolated spurs
- Halo contribution < 10% of disc

Axial Ratio Test: Compare Data to Model

Singal et al 2015
Remarkably tight correlation exists between radio and far-IR emission.

If high-latitude Galaxy is bright in radio, it should also be bright in the far-IR.

But it’s not ...

Two tests:

- DIRBE x canonical Radio/FIR ratio
- Scale observed radio/FIR to $|b|=90$

Obtain $T \sim 5K$ at 408 MHz: Too Small!
Local (Nearby) Origin

If we were inside spherical bubble with uniform field ...

- Predicted amplitude $\sim 400 \, \mu K$ at 23 GHz
- Typical polarization fraction $f \sim 0.25$
- Expect polarized quadrupole $\sim 100 \, \mu K$ (not seen)
Depolarization

**The observed radio sky is strikingly depolarized**

Although synchrotron emission is inherently highly polarized (fractional polarization $p \sim 0.7$), half the synchrotron sky shows $p < 0.05$.

Crude estimate:
- Simulate turbulent magnetic field
- Intensities add, polarizations cancel
- How many independent cells needed to depolarize?

**Problem:**
- Simulations show $>10^4$ cells required
- Mean cell diameter <0.05 pc
- Ratio of turbulent/mean field too high!
Fractional Polarization

In which we play with the denominator ...

Two problems:

- Faintest 50% of sky is depolarized
- Bright features more polarized than dim

Suppose we remove the isotropic part from the denominator of this equation ...
Fractional Polarization

*In which we play with the denominator ...*

\[
\frac{\text{Polarized Intensity}}{\text{Unpolarized Intensity}} = \text{Fractional Polarization}
\]

**Problem solved?**
- Fractional polarization now 10%—30%
- Broad overlap between bright/dim regions

Suppose we remove the isotropic part from the denominator of this equation ...
NOW what?

Having efficiently ruled out a number of "most plausible" origins, what comes next?

Diagram: Galactic and Extragalactic origins, with further subdivisions into nearby, distant, discrete, and diffuse categories. Problems include polarization, Far-IR correction, unique halo X-ray limit, source density, Far-IR correction, and source amplitude.
Future Directions

Low-frequency surveys have substantial uncertainty
Dominated by zero-level errors

ARCADE has small errors, but limited coverage
Synchrotron polarization not well mapped in faintest parts of sky

**Solution 1:** Map sky at frequency where sky temperature matches ground temperature

\[ \nu \sim 120 \, \text{MHz} \]

\[ T_{\text{sky}} \sim 300 \, \text{K} \]

Don’t need great angular resolution

**Solution 2:** Map sky at frequency where zero level is already well established

\[ \nu \sim 3.15 \, \text{GHz (ARCADE)} \]

Improve ARCADE resolution & sky coverage

**Solution 3:** Nail down synchrotron amplitude and polarization
Faraday rotation \(\rightarrow\) Frequencies > 5 GHz
CBASS, PIXIE, ...
Parting Thoughts

Radio sky contains significant monopole
• Amplitude ~ 11K at 408 MHz
• Spectral index -2.6

What is it??

Looking for a (synchrotron) source that's
• Isotropic
• Depolarized
• Uncorrelated with far-IR / other tracers

But not unique to Milky Way
There are more things in heaven and Earth, Horatio, Than are dreamt of in your philosophy
Shakespeare (Hamlet)
# Measurement Uncertainty

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Background Temperature</th>
<th>Zero Level</th>
<th>Gain</th>
<th>Absolute Uncertainty</th>
<th>Fractional Uncertainty</th>
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</thead>
<tbody>
<tr>
<td>22 MHz</td>
<td>22,000 K</td>
<td>5000 K</td>
<td>5%</td>
<td>5100 K</td>
<td>23%</td>
</tr>
<tr>
<td>45 MHz</td>
<td>3400</td>
<td>250</td>
<td>10%</td>
<td>420</td>
<td>12%</td>
</tr>
<tr>
<td>408 MHz</td>
<td>11</td>
<td>0.9</td>
<td>10%</td>
<td>1.4</td>
<td>13%</td>
</tr>
<tr>
<td>1420 MHz</td>
<td>0.43</td>
<td>0.5</td>
<td>5%</td>
<td>0.5</td>
<td>116%</td>
</tr>
<tr>
<td>3.15 GHz</td>
<td>0.056</td>
<td>0.003</td>
<td>0.01%</td>
<td>0.003</td>
<td>5%</td>
</tr>
</tbody>
</table>
Origins and Issues

Radio Background is ...

Galactic
- Nearby
- Distant

Extragalactic
- Discrete
- Diffuse

Problems
- Polarization Far-IR corr
- Unique Halo X-ray limit
- Source Density Far-IR corr
- Source Amplitude X-ray limit
Radio Halo Model

Anisotropic Galactic sources

Simplified source distribution (viewed from Solar circle)

Simplified source distribution (viewed by external observer)

Singal et al 2015