Cosmic Rays & Multi-Messenger Opportunities in Starbursts

Tova M. Yoast-Hull
Canadian Institute for Theoretical Astrophysics

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In This Talk ...

- Why Starburst Galaxies?
- Modeling Cosmic Rays
  - Radio, Gamma-Rays, & Neutrinos
- Lessons from Starbursts
  - Cosmic Ray Connections to Galaxy Evolution
I. What's Up With Starburst Galaxies
High Energy Cosmic Rays

- What are the sources of high energy cosmic rays?
- Where are astrophysical neutrinos being produced?
- How does environment affect cosmic ray populations?
CMZs in starburst galaxies are characterized by:

- Radius ~ 100 to 300 pc
- Large amounts of dense molecular gas
- Strong magnetic fields and intense radiation fields
- High and highly variable star-formation rates
Star Formation in CMZs

- Kennicutt-Schmidt correlation breaks down in CMZs
  - SFR in Galactic Center is down by factor of ~10 from predicted
- Many nearby starbursts with similar gas densities and SFRs
  - Only a couple detected in gamma-rays

Starburst Galaxy: NGC 253

Galactic Center
High Redshift Analogues

- Star formation at high redshift galaxies is very clumpy.
  - Can study nearby galaxies to learn about similar environments.
II. A History of Cosmic Ray Models
1980s & 1990s: New Discoveries

- First investigations into the far-infrared – radio correlation (de Jong+ 1985, Helou+ 1985)

- EGRET launches in 1991


EGRET all-sky map of gamma rays above 100 MeV
Early Cosmic Ray Models

● **Late 1980s:**
  − FIR-radio correlation
  − New radio observations of starbursts
  − Minimum energy magnetic field estimates

● **Early 1990s:**
  − CR propagation models connected to radio emission from starbursts
  − Predictions for detection of M82 with EGRET in gamma-rays

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Early Multiwavelength Observations

- Radio observations of CMZs
- Gamma-ray upper-limits from EGRET.


Basics of Cosmic Ray Models

- CR transport equation:
  \[
  \frac{N(E)}{\tau(E)} - \frac{d}{dE} \left[ b(E)N(E) \right] - Q(E) = 0
  \]

- CR source function:
  \[
  \int Q(E)E dE = \frac{\eta \nu_{SNR} E_{51}}{V}
  \]

- CR lifetimes:
  \[
  \tau^{-1} = \tau_{\text{diff}}^{-1} + \tau_{\text{adv}}^{-1} + \tau_{\text{loss}}^{-1}
  \]

- Secondary CRs / γ-rays, ν:
  \[
  q(E) \propto \int \frac{d\sigma(E, E_\nu)}{dE_\nu} N_\nu(E_\nu) dE_\nu
  \]
Cosmic Rays & Gamma-Rays in M82


Yoast-Hull+, 2013, 2015

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FIR – Gamma-Ray Correlation


Cosmic Rays & Neutrinos

Waxman 2015, arXiv 1511.00815


Bechtol+ 2015, arXiv 1511.00688
III. A Window into Galaxy Evolution
Energy Densities in CMZs


Tova M. Yoast-Hull
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SNRs in our Galaxy accelerate CRs up to $\sim 10^{14}$ eV energies.

Magnetic fields in starbursts range from $\sim 100 \, \mu$G to $\sim 10$ mG.
Galactic Feedback:
- ISM heating by cosmic rays
- Cosmic ray driven winds

FIR-Radio Correlation
Summary

- **Starburst Galaxies:**
  - Sites of intense star-formation and high rates of cosmic ray interactions.
  - Potentially sources of very high energy to ultra high energy CRs and astrophysical neutrinos.

- **Radio + Gamma-Rays:**
  - Combination of these observations are very powerful in constraining CR & ISM properties.
  - Many new telescopes (CTA, SKA) will be important for CR studies.

- **Galaxy Evolution:**
  - Nearby galaxy examples demonstrate impact of CRs on ISM & IGM; useful for high redshift studies.