The Multiwavelength Properties of Arp 220
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In This Talk ...

- The Interstellar Medium of Arp 220
- Non-Thermal Detections
- Radio & Gamma-Ray Disconnect
Observational Information

- **Radio**
  - CR electrons, magnetic fields

- **Millimeter**
  - Molecular gas content

- **Infrared**
  - Radiation field
  - Dust temperatures

- **Optical**
  - ISM pressures, winds

- **X-Rays**
  - Hot gas content, winds

- **Gamma-Rays**
  - CR protons & electrons, ISM density

- **Neutrinos**
  - CR protons & ISM density

Muxlow+ 1995, L-Band MERLIN Image
M82 Core – Radio Continuum
Essential Properties of Arp 220

- Closest Ultra-Luminous Infrared Galaxy (ULIRG)
- Late stage merging galaxy
  - Two nuclei separated by ~ 1” ~ 370 pc.
  - Nuclei are embedded in counter-rotating disk
- ISM properties:
  - $L_{\text{FIR}} \sim 10^{11.5-12.5} \, L_\odot \sim 10^{45} \, \text{erg/s}$
  - $M_{\text{H}_2} \sim 10^9 \, M_\odot$
  - $B \sim \text{few mG}$
The Central Nuclei of Arp 220

- Power from star formation:
  - SFR $\sim 200 \, M_\odot \, yr^{-1}$
  - SN Rate $\sim 2 - 4 \, yr^{-1}$
  - See SNRs with VLBI
- Power from an AGN?
  - Observations of centers hindered by dust obscuration
  - The usual indicators for AGN are not applicable.
    - mm emission lines
    - dust temperature
    - X-rays

LOFAR 150MHz
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Fraction of SN Energy into CRs: 
\[ \int_{E_{\text{min}}}^{E_{\text{max}}} Q(E) E \, dE = \frac{\eta \nu_{\text{SN}} E_{51}}{V} \]

Proton to Electron Ratio: \[ \eta \sim 0.05 - 0.2 \]

\[ \frac{Q_p}{Q_e} = 50 \]

SNRs are primary CR accelerators.
Secondary e+/− are included in all leptonic emission calculations.
\( U_B \) and \( U_{CR} \) are not assumed to be coupled.

# Arp 220 Nuclear Properties

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<tr>
<th></th>
<th>East</th>
<th>West</th>
<th>CND</th>
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<tbody>
<tr>
<td><strong>Radius (pc)</strong></td>
<td>70</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td><strong>SN Rate (yr⁻¹)</strong></td>
<td>0.7</td>
<td>0.7</td>
<td>1.4</td>
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<tr>
<td><strong>FIR Luminosity (L☉)</strong></td>
<td>$3 \times 10^{11}$</td>
<td>$3 \times 10^{11}$</td>
<td>$6 \times 10^{11}$</td>
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<tr>
<td><strong>Molecular Mass (M☉)</strong></td>
<td>$6 \times 10^{8}$</td>
<td>$4 \times 10^{8}$</td>
<td>$6 \times 10^{8}$</td>
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Radio Synchrotron Predictions

- Achieve good fits to the radio spectra for both nuclei based on observed supernova rate.
- Gamma-ray predictions fall short of the *Fermi* observations.
- How much additional energy into cosmic rays is necessary to match gamma-rays?

Gamma-Rays Implications

Gamma-Ray Implications

Cosmic Ray Electrons

- Competitive energy loss processes:
  - Bremsstrahlung
  - Inverse Compton
  - Synchrotron

\[-\left(\frac{dE}{dt}\right)_{e,\,brem} \propto n_{\text{ISM}} E_e\]

\[-\left(\frac{dE}{dt}\right)_{e,\,IC} \propto U_{\text{rad}} E_e^2\]

\[-\left(\frac{dE}{dt}\right)_{e,\,synch} \propto U_B E_e^2\]

• Increase in molecular gas mass of factor of $>10$ is necessary to match the observed radio emission.
• Increase this large is unphysical.
Radiation Field Energy Density

\[ U_{IR} = \frac{\tau L_{IR}}{4\pi R^2 c} \]

Yoast-Hull+ 2017, In prep
Radiation Field Energy Density

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Gamma-Rays (Combined)

Radio (Western Nucleus)

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Conclusions

- There is an overabundance of gamma-rays compared to the radio (and the SFR).
- CR energy requirements for the gamma-rays are factors of 4 – 8 larger than suggested by observations.
- To lower the radio emission, IR opacities of 5 – 1000 are necessary.
- Further testing of the radio models (particularly the thermal component) is required.

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