Non-thermal Diffuse Emission in NGC 253 from Hard X-rays to TeV Gamma Rays*

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The Life of a Cosmic Ray

\[
\frac{\partial N(E)}{\partial t} = D \nabla^2 N(E) + \frac{\partial}{\partial E} [b(E)N(E)] - \frac{N(E)}{\tau(E)} + Q(E)
\]

Sources
- Escape Losses
- Synchrotron
- Inverse Compton
- \(\pi^0\)-decay
- Bremsstrahlung

Cooling Losses
- Inverse Compton
- Synchrotron
- \(\pi^0\)-decay

Escape Losses
- Interstellar Atomic Nuclei
- Shock Front
- Disrupted Magnetic Field Lines

Image credit: George Kelvin
The Life of a Cosmic Ray

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Sources
- Supernova Rate
- Acceleration Efficiency
- Primary Spectrum

Escape Losses
- Diffusion
- Starburst Wind (Advection)
- Annihilation (positrons)

Cooling Losses
- Interstellar Medium
- Interstellar Radiation Field
- Magnetic Field

Image credit: George Kelvin

Image credit: Image Credit: M. Blecha
Cosmic Rays in Starburst Galaxies

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Cosmic Rays in Starburst Galaxies

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Non-thermal Diffuse Emission in Starburst Galaxies

\[ N(E) \quad n_{\text{phot}}(E) \quad n_{\text{ISM}}(E) \quad B^2 \]
The typical rest-frame energy of upscattered CMB light is the redshift where the scattering takes place. Thus the cascade spectrum observed at redshift $z$ may not cascade. However, since most $\gamma$-ray lines (grey lines), bremsstrahlung (short-dashed), IC (dotted), and TeV energies. Nearly 1 $\times 10^{10}$ erg s$^{-1}$ from the X-ray luminosity spectrum of NGC 253's starburst, compared to the $\gamma$-ray luminosity spectrum of M82 and NGC 253. We note that the IC cooling time for the M82 and NGC 253 is the same as in M82 and NGC 253.

The key ingredients in this calculation are the UV-IR background effectively stops IC, and quenches the cascade. Within the redshift step, the UV-IR background effectively stops IC, and quenches the cascade. The cascade spectrum observed at redshift $z$ is the redshift where the scattering takes place. Thus the cascade spectrum observed at redshift $z$ may not cascade. However, since most IC cooling time for the M82 and NGC 253 is the same as in M82 and NGC 253.

Lacki et al. 2012

Leptonic Model

Hadronic Model

Lacki et al. 2012
Imaging Capability in Hard X-rays

NGC 253 Optical

Swift BAT (14--20 keV)

Chandra

0.5--2 keV
2--4 keV
4--7 keV
Imaging Capability in Hard X-rays
NuSTAR, Chandra, and V L B AO observation of NGC 253.}

F IG. 4. — PSF-convolved point source images from top to bottom: 4-25 keV, 4-6 keV, 6-12 keV, and 12-25 keV. In the leftmost panels, the image displays the smoothed, background-subtracted counts data from all 3 epochs, with the overlaid yellow contour following the data image. The middle panels show the best-fit model (described in Section 4.1.1) with the same color scale as the data, and the white contours (also reproduced in the left and right panels) follow the underlying smoothed model image. In the right panels, the residual of the other two panels (data − model) is displayed with its own, smaller scale given by the associated color bar. All images have been smoothed by a Gaussian kernel of 2 pixels (∼5′′), and the contours have square-root spacing between the minimum and maximum values of the model images; both the yellow (data) and model (white) contours follow identical intensities. During fits, the raw data (left) is compared to the model (middle), which includes a component for the background as well as for each point source, and the pre-determined position and PSF shape of sources remain fixed during fits. In the left panels, note how well the white contours track the yellow contours, even where the signal-to-noise is only moderately high, which is only possible thanks to the excellent PSF calibration of the NuSTAR telescopes. The lack of significant structure in the residual images also demonstrates the success of the fitting process and suggests we have identified all detectable sources of emission in the central 7.4′ (8.5 kpc) of NGC 253.

Wik et al. 2014 NuSTAR's Look at NGC 253
NuSTAR Constraints on Inverse Compton

Leptonic Model

Hadronic Model

Wik et al. 2014
**Future Work**

### Escape Losses

- Diffusion
- Starburst Wind (Advection)
- Annihilation (positrons)

### Sources

- Supernova Rate
- Acceleration Efficiency
- Primary Spectrum

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**Equation**

\[
\frac{\partial}{\partial E} \left[ b(E)N(E) \right] = \frac{N(E)}{\tau(E)} - Q(E)
\]

**Table 1: Results of maximum likelihood analyses of M82 and NGC 253.**

<table>
<thead>
<tr>
<th></th>
<th>RA</th>
<th>Dec</th>
<th>(r_{95})</th>
<th>((E/100 \text{MeV})^{\text{photon index}})</th>
<th>(\text{significance})</th>
</tr>
</thead>
<tbody>
<tr>
<td>M82</td>
<td>149.06</td>
<td>69.64</td>
<td>0.11</td>
<td>1.6 ± 0.5 stat ± 0.3 sys ± 2.2 stat ± 0.05 sys</td>
<td>6.8 ± 0.2</td>
</tr>
<tr>
<td>NGC 253</td>
<td>11.79</td>
<td>-25.21</td>
<td>0.14</td>
<td>0.6 ± 0.4 stat ± 0.4 sys ± 1.95 stat ± 0.05 sys</td>
<td>4.8 ± 0.4</td>
</tr>
</tbody>
</table>

**Source localization results (J2000) with \(r_{95}\) corresponding to the 95% confidence error radius around the best-fit position.**

**Parameters of power-law spectral models fitted to the data:** Integrated photon flux \((E/100 \text{MeV})^{\text{photon index}}\) and photon index.

**Detection significance of each source.**

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**Future Work**

- Image credit: George Kelvin

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### Escape Losses

- Interstellar Medium
- Interstellar Radiation Field
- Magnetic Field

**Cooling Losses**

- Low-energy photon
- Inverse Compton
- Bremsstrahlung
- \(\pi^0\)-decay

**Synchrotron**

- Charged particle (proton or electron)
- Magnetic field

**Inverse Compton**

- Electron
- X-ray
Summary

❖ With its enhanced imaging capability in hard X-rays, NuSTAR has placed the deepest constraint to date on the Inverse Compton emission in NGC 253.

❖ Further modeling in light of the NuSTAR constraint and updated observations from Fermi and HESS will allow us to constrain the physical parameters of NGC 253 (e.g., cosmic ray energy density, magnetic field, etc.).

❖ Similar analyses and modeling will be performed using existing and upcoming observations for M82.