Radio synchrotron spectra of star-forming galaxies

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What is the shape of the synchtron spectrum?
Synchrotron and thermal emission

Radio spectra of galaxies consist of

- Synchrotron emission
- Thermal radio emission (typically 10% at 1 GHz)

For a reliable separation between them we need observations with

- A large frequency range
- High frequency data (> 10 GHz)

We use a sample of **14 star-forming galaxies** with data between **300 MHz** (below absorption can become relevant which we do not consider) and **≈ 23 GHz** (Effelsberg)

**Sample:**

**Dwarf galaxies:** II Zw 40, II Zw 70, IC 10, NGC 1569, NGC 4449

**Interacting galaxies:** NGC 4490/85, M51, NGC 4631

**Merging galaxies:** NGC 4038/39, NGC 6052

**Starburst galaxies:** NGC 2146, M82, NGC 3079, NGC 3310
Model for synchrotron emission

SN explosion produces relativistic electrons with \( S(v) = A v^{-\alpha_{\text{inj}}} \), with \( \alpha_{\text{inj}} \approx 0.5 \)

Some relativistic electron “escape” from the halo

Galactic disk

Galactic halo, \( B \neq 0 \)

Relativistic electrons propagate away, loosing energy via:

- Synchrotron losses
- Inverse Compton losses
- Bremsstrahlung
- Adiabatic losses

Steepens synchrotron spectrum by 0.5

Do not steepen synchrotron spectrum
We used 4 simple but realistic models, trying to cover a large range of curvatures:

1. **Constant synchrotron spectrum**
2. **Curved synchrotron spectrum** due to different energy losses: Change in slope of 0.5, but over many orders of magnitude
3. **Break in the synchrotron spectrum** due to escape: Relativistic electrons emitting above $\nu_{\text{break}}$ have suffered energy losses, relativistic electrons emitting below $\nu_{\text{break}}$ have not.
4. **Exponential cutoff**: No relativistic electron above $E_{\text{break}}$
Different models used for the fit

<table>
<thead>
<tr>
<th>Model name</th>
<th>Radio spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>( S_{th,0} \left( \frac{\nu}{\nu_0} \right)^{-0.1} + S_{nth,0} \left( \frac{\nu}{\nu_0} \right)^{-\alpha_{nth}} )</td>
</tr>
<tr>
<td>curved</td>
<td>( S_{th,0} \left( \frac{\nu}{\nu_0} \right)^{-0.1} + S_{nth,0} \left( \frac{\nu}{\nu_0} \right)^{-\alpha_{nth}} \left[ 1 - \left( 1 - \sqrt{\frac{\nu}{\nu_b}} \right)^{g_{inj}^{-1}} \right] ) for ( \nu \leq \nu_b )</td>
</tr>
<tr>
<td>break</td>
<td>( S_{th,0} \left( \frac{\nu}{\nu_0} \right)^{-0.1} + S_{nth,0} \left( \frac{\nu}{\nu_0} \right)^{-\alpha_{nth} - 0.5} \left[ 1 - \left( 1 - \sqrt{\frac{\nu}{\nu_b}} \right)^{g_{inj}^{-1}} \right] ) for ( \nu &gt; \nu_b )</td>
</tr>
<tr>
<td>cutoff</td>
<td>( S_{th,0} \left( \frac{\nu}{\nu_0} \right)^{-0.1} + S_{nth,0} \left( \frac{\nu}{\nu_0} \right)^{-\alpha_{nth}} e^{-\frac{\nu}{\nu_b}} )</td>
</tr>
</tbody>
</table>
Some examples for best-fit

- Constant and curved synchrotron spectra were almost indistinguishable.
- Only dwarf galaxies with a high thermal fraction had constant synchrotron spectra as a best fit, but the shape of synchrotron spectrum was not well constrained.
• In 11 galaxies a strongly curved synchrotron spectrum was necessary (break or cut-off).
• Steepening and subsequent flattening was directly visible in several 5-7 cases.
Table 3. Fit results

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>(S_{tot}, \text{1 GHz} [\text{mJy}])</th>
<th>(f_{th}, \text{1 GHz})</th>
<th>(\alpha_{nth})</th>
<th>(v_b, \text{GHz})</th>
<th>(\chi^2_v)</th>
<th>best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>II Zw 40</td>
<td>32</td>
<td>0.80</td>
<td>0.35</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>II Zw 70</td>
<td>5.2 ± 0.2</td>
<td>0.62 ± 0.03</td>
<td>1.15 ± 0.12</td>
<td>–</td>
<td>0.33</td>
<td>constant</td>
</tr>
<tr>
<td>IC 10</td>
<td>446 ± 40</td>
<td>0.21 ± 0.07</td>
<td>0.58 ± 0.08</td>
<td>–</td>
<td>0.18</td>
<td>constant</td>
</tr>
<tr>
<td>NGC 1569</td>
<td>494 ± 12</td>
<td>0.22 ± 0.02</td>
<td>0.42 ± 0.02</td>
<td>12.4 ± 2.4</td>
<td>0.12</td>
<td>cutoff</td>
</tr>
<tr>
<td>NGC 4449</td>
<td>342 ± 32</td>
<td>0.27 ± 0.03</td>
<td>0.40 ± 0.08</td>
<td>4.7 ± 0.9</td>
<td>0.17</td>
<td>cutoff</td>
</tr>
<tr>
<td>NGC 4490</td>
<td>1051 ± 206</td>
<td>0.13 ± 0.04</td>
<td>0.57 ± 0.09</td>
<td>6.8 ± 1.4</td>
<td>0.20</td>
<td>cutoff</td>
</tr>
<tr>
<td>NGC 4631</td>
<td>1637 ± 75</td>
<td>0.14 ± 0.01</td>
<td>0.57 ± 0.03</td>
<td>6.6 ± 0.4</td>
<td>2.08</td>
<td>cutoff</td>
</tr>
<tr>
<td>NGC 5194</td>
<td>1788 ± 464</td>
<td>0.11 ± 0.03</td>
<td>0.67 ± 0.10</td>
<td>7.2 ± 0.6</td>
<td>0.62</td>
<td>cutoff</td>
</tr>
<tr>
<td>NGC 4038</td>
<td>683 ± 160</td>
<td>0.13 ± 0.04</td>
<td>0.71 ± 0.09</td>
<td>8.2 ± 3.8</td>
<td>0.01</td>
<td>break</td>
</tr>
<tr>
<td>NGC 6052</td>
<td>129 ± 10</td>
<td>0.08 ± 0.01</td>
<td>0.56 ± 0.04</td>
<td>2.4 ± 0.5</td>
<td>0.32</td>
<td>break</td>
</tr>
<tr>
<td>NGC 2146</td>
<td>1359 ± 18</td>
<td>0.16 ± 0.01</td>
<td>0.51 ± 0.02</td>
<td>6.2 ± 0.5</td>
<td>0.47</td>
<td>cutoff</td>
</tr>
<tr>
<td>NGC 3034</td>
<td>9043 ± 175</td>
<td>0.14 ± 0.01</td>
<td>0.40 ± 0.02</td>
<td>11.2 ± 1.0</td>
<td>0.45</td>
<td>cutoff</td>
</tr>
<tr>
<td>NGC 3079</td>
<td>1111 ± 104</td>
<td>0.10 ± 0.02</td>
<td>0.74 ± 0.01</td>
<td>9.0 ± 2.0</td>
<td>1.59</td>
<td>break</td>
</tr>
<tr>
<td>NGC 3310</td>
<td>470 ± 16</td>
<td>0.19 ± 0.01</td>
<td>0.60 ± 0.03</td>
<td>1.2 ± 0.3</td>
<td>0.40</td>
<td>break</td>
</tr>
</tbody>
</table>
The fitted low-frequency spectral index is consistent with the radio spectral index of supernova remnants (from Green 2014).

SNR:
\[
<\alpha_{\text{SNR}} > = 0.50 \\
\sigma_{\text{SNR}} = 0.33
\]

Fit for 14 galaxies:
\[
<\alpha_{\text{Gal}} > = 0.59 \\
\sigma_{\text{Gal}} = 0.20
\]
Conclusions

• We found **sharply curved synchtron spectra** in 11 star-forming galaxies, 3 objects the shape of the synchtron spectrum was undetermined due to a dominant thermal radio fraction.

• Indication of a convective wind?

• **Spatially resolved spectra of the halo emission** are necessary to search for signatures of energy losses.

• A high sensitivity and spatial resolution is crucial ➔ **SKA**
Thank you for your attention!
Thermal fraction

![Graph showing the thermal fraction versus log $L_k [L_\odot]$]
The ratio of thermal radio to Hα emission allows to determine the extinction suffered by the Hα line.

In Zw 40 and IC 10 most likely the – very high - Galactic extinction has been overestimated.