High Radio-frequencies Spectra of SNR IC443 and W44
Evidence for a wide electron spectra scatter among different SNR regions?

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IAU Symposium 331: SNR 1987A, 30 years later
Outline of our research:

Spectral studies of large SNRs through single-dish imaging at high-frequencies (1-20 GHz) with the 64m Sardinia Radio Telescope (SRT).

People:

E.Egron, M.N.Iacolina, S.Loru, M.Marongiu, S.Righini, M.Cardillo, A.Giuliani, S.Mulas & SRT Team
Hadron and lepton gamma-ray emission. Cosmic rays acceleration.

Figure S2: The spectral energy distribution of IC 443 with a model in which electron bremsstrahlung is the dominant radiation process in the gamma-ray band (dashed line and dash-dotted as in Figure 2). In the radio band the dominant radiation process is synchrotron emission. The parameters used in the calculation for the dashed curve are $s_1 = 1.72$, $s_2 = 3.2$, $p_{br} = 10^5$ eV $c^{-1}$, $B = 50$ $\mu$G, and $n = 300$ $c$ $m^{-3}$, and $W_e = 5 \times 10^{47}$ erg ($E > 1$ $G e V$ $c^{-1}$). The dash-dotted curve indicates the same model but with an abrupt low-energy break in the electron spectrum at 300 MeV $c^{-1}$. For comparison the best-fit pion-decay model is shown as a solid line. The dotted line shows a combined bremsstrahlung and pion-decay model in which $K_{ep} = 0.01$ to demonstrate that such a model is consistent with the data.

Radio data are taken from (39).

Multifrequency spectrum of SNR IC443

Ackermann et al., 2013
At which frequency SNR radio spectra break?

Only limited information on spatially resolved SNR spectra above 5 GHz available so far!
One-region models based on Integrated flux: oversimplification
Multi-region models based on spatially resolved spectra: imaging!

IC443
SRT 7 GHz
Imaging of large SNRs as W44 and IC443 through radio interferometric observations provides a wealth of information about their structures, but flux estimation can be an issue:

**Single dish radio imaging** with good resolution can provide accurate flux density measurements then accurate integrated spectra.
IC443

1.5 GHz

134 +/- 4 Jy

7 GHz

67 +/- 3 Jy

Spectral index $\alpha=0.46 +/- 0.03$ ($S=k^{-\alpha}$)

A standard shock spectrum?

Egron et al., submitted
IC443: integrated spectra

$\alpha = 0.46 \pm 0.03$ (SRT data 1.5-7 GHz)

Egron et al., submitted

$\alpha = 0.36 \pm 0.02$ (0.02-10 GHz)

Castelletti et al. (2011)
IC443: integrated spectra

\[ \alpha = 0.46 \pm 0.03 \quad \text{(SRT data 1.5-7 GHz)} \]

Egron et al., submitted

\[ \alpha = 0.47 \pm 0.06 \quad \text{(1.39-8 GHz, literature)} \]


\[ \alpha = 0.33 \pm 0.01 \quad \text{(0.02-1.0 GHz, literature)} \]

W44

\[ \text{214} \pm 6 \text{ Jy} \quad \text{94} \pm 4 \text{ Jy} \]

\( \text{Spectral index } \alpha = 0.55 \pm 0.03 \)
W44: integrated spectra

\[ \alpha = 0.55 \pm 0.03 \] (SRT data 1.5-7.2 GHz)

\[ \alpha = 0.36 \pm 0.02 \] (0.02-1.0 GHz, literature)

Measurements from Roger et al. (1986), Kassim (1989), Castelletti et al. (2007),
Kovalenko et al. (1994), Edge et al. (1958), Bennett (1963), Kellermann et al. (1969),
Davis et al. (1965), Large et al. (1961), Kesteven (1968), Clark et al. (1975), Dickel &
Denoyer (1975), Kuz’min (1962), Moran (1965), Kellermann et al. (1969), Pauliny-Toth
et al. (1966), Harris (1962), Wilson (1963)

Egron et al., submitted
IC443
Low-frequency $\alpha=0.46 \pm 0.03$ (SRT data 1.5-7 GHz)
High-frequency $\alpha=0.33 \pm 0.01$ (0.02-1.0 GHz, literature)

W44
Low-frequency $\alpha=0.55 \pm 0.03$ (SRT data 1.5-7.2 GHz)
High-frequency $\alpha=0.36 \pm 0.02$ (0.02-1.0 GHz, literature)

Evidence for a spectral turnoff around 1 GHz?
(4$\sigma$, $\Delta\alpha=0.1$)
Steepening of the primary particle spectrum at 10 GeV for W44 and 100 GeV for IC443 \(\rightarrow\) synchrotron breaks at >10 GHz (Cardillo et al. 2014; Ackermann et al. 2013; Giuliani et al. 2011)
What is the possible origin of a turn-off at 1 GHz?

Hadronic interaction $\rightarrow$ secondary electrons

Secondary hadronic electrons:
- A major fraction of the whole leptonic plasma?
- Expected to take 10% of the primary particle energy?

(see Cardillo et al., 2016; Lee et al. 2015)

What about the primary particle break $>10$ GHz?
W44

See Loru et al. Poster
Summary of integrated spectra

W44: $\alpha = 0.36 \rightarrow \alpha = 0.55 \rightarrow \alpha = 0.9$

turn-offs 1 GHz 10 GHz

hadronic $e^-$ primary $e^-$

IC443: $\alpha = 0.33 \rightarrow \alpha = 0.46 \rightarrow \alpha = ?$

turn-offs 1 GHz ？ GHz

hadronic $e^-$ primary $e^-$

On-going analysis at 21 GHZ....
Need for spatially-resolved spectra

The assumption of a single primary (and secondary) electron population is too simplistic for modelling: different region-dependent (SNR/PWN) electron populations are present.
W44
Integrated spectra: OK
Spectral Imaging: POOR

IC443

Egron et al., submitted
**W44**

Integrated spectra: OK

Spectral Imaging: OK!

**IC443**

Loru et al., in preparation
Spectral index map: IC443

Bright regions $\rightarrow$ flat spectra,
Faint regions and halo $\rightarrow$ steep spectra up to $\alpha=0.7$
Bright regions $\rightarrow$ flat spectra,
Faint regions and halo $\rightarrow$ steep spectra up to $\alpha=0.7$
Spread in spectral index distribution → several concurring processes?

Region dependent thermal absorption (free-free)?

it explain the low-frequency cut-off (<50 MHz) observed in the integrated SNR spectrum of IC443 (Castelletti et al., 2011), but extrapolating optical depth peak (τ_{74}=0.3 at 74 MHz) to >1 GHz the absorption coefficients are negligible exp(-τ_{74} (v/74 MHz)^{-2.1}).
Spread in spectral index distribution → several concurring processes?

Intrinsic variety in the primary and secondary electron spectra (spectral slopes and breaks)?

Standard shock acceleration theory: expected synchrotron slope $\alpha=0.5$ (compatible with our average values) or at least $\alpha>0.2$ even in the ultrarelativistic regime and assuming a high shock compression factor (Ellison et al., 1996, 1995; Sturner et al., 1997).

Cannot explain flat spectra!
Spread in spectral index distribution → several concurring processes?

Flattening effect due to region-dependent amount of secondary electrons production?

Significant amount of secondary electrons where enhanced hadronic emission is present (Cardillo et al., 2016). Gamma-ray emission clearly correlates with bright radio rims and filaments for W44.
Spread in spectral index distribution → several concurring processes?

Strongly-enhanced, region-dependent cooling?

No significant steepening of the spectral index due to synchrotron cooling is expected from a particle gas drifting away from the shock region on a time scale of $10^4$-10$^5$ years (Sturner et al. 1997).

Region-dependent spectral slopes could reflect the presence of different electron distribution cut-off energies.
Spread in spectral index distribution → several concurring processes?

Region dependent thermal absorption (free-free)?

Intrinsic variety in the primary and secondary electron spectra (spectral slopes and breaks)?

Flattening effect due to region-dependent amount of secondary electrons production?

Strongly-enhanced, region-dependent cooling?

Region-dependent spectral slopes could reflect the presence of different electron distribution cut-off energies?
Integrated spectra: OK
Spectral Imaging: POOR
Egron et al., submitted
Single dish radio imaging with good resolution can provide accurate flux density measurements, then accurate integrated spectra.

Poor spatially-resolved spectra are obtained when combining SRT L(1.5 GHz) + C(7 GHz) band...
...but improving when combining C(7 GHz) band and K(20 GHz) band measurements.
W44

Integrated spectra: OK

Spectral Imaging: OK!

IC443

Loru et al., in preparation

21 GHz

7 GHz
The *Sardinia Radio Telescope* can provide high-resolution imaging (and then spatially resolved spectra) up to 22 GHz suitable for multi-wavelength modeling of large diffuse sources (see also Loru et al. Poster).

High-frequency spatially resolved spectra can better constrain cosmic-rays emission from SNR.
Thank-you!