Low Frequency Absorption in Cassiopeia A

LOFAR Status Meeting

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Bright sources in the LBA

- Commissioning 2015 proposal, Legacy A-team observations
- Initial motivation was to create high resolution models for demixing
- Full synthesis, simultaneous calibrator observations, international stations

For Cas A, roughly,

$$S_\nu = 2720 \left(\frac{\nu}{1\mathrm{GHz}}\right)^{-0.77} \mathrm{Jy} \tag{1}$$

$$S_{30\mathrm{MHz}} \sim 40,000\mathrm{Jy}! \tag{2}$$

Figure: Everyone here is familiar with the A-team...

Observations

Observation details

Calibrator	Time	Stations	Freq. Resolution
3C380	8 hr	CS, RS, int. *	64 ch/sb

Calibration Strategy

1. Demix Cyg A, average to 4 ch/sb, 2 s
2. Correct for the beam in linear coordinates
3. Convert to circular coordinates and calibrate diagonally (69 MHz model of Oonk *et al.*, 2017)
4. Image, selfcal, repeat

Wide Band Image

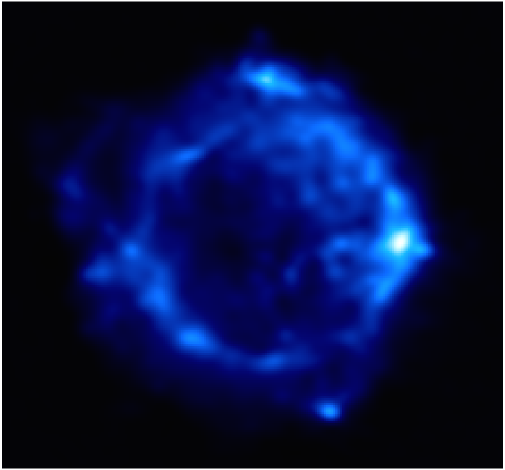
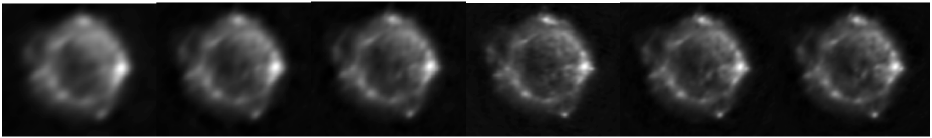


Figure: Cassiopeia A in the *LOFAR* LBA. Central frequency is 54 MHz, beam size is 10 arcsec, noise is 0.01 Jy/bm, and dynamic range is of 13,000.

Narrow Band Images

To study absorption we want to look at localized spectral variations

- S/N so high that can make images of a few (~ 5) subbands.
- Images every 5 MHz
- Common uv range of 500 to 12000 (7 arcmin to 17 arcsec; source is 5 arcmin)
- Bootstrapped flux



1 MHz images of Cassiopeia A in the *LOFAR* LBA. From left to right, 30, 40, 50, 60, 70, and 77 MHz

Spectral Index Map

A spectral index map is useful, but misses part of the spectral information.

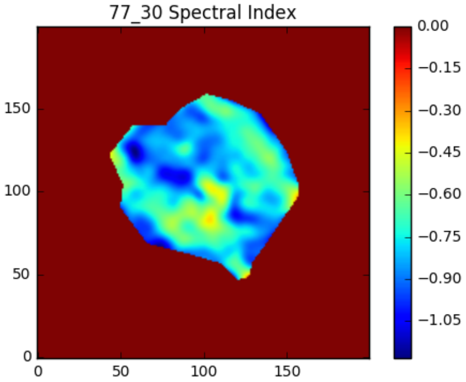


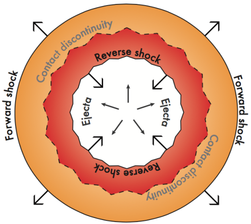
Figure: Spectral index map made from 30 MHz and 77 MHz images. 17 arcsec resolution.

The Reverse Shock in Cas A

Supernova blast wave + circumstellar material → reverse shock
(= propagates interior to the forward shock)

Shocked gas: $T \sim 10^7$ K
Unshocked ejecta at $T \sim 100$ K that has not been heated by the reverse shock. Probed by:

- IR lines
- Decay of radioactive elements (Ti^{44})
- Low frequency free-free absorption



Free-free absorption

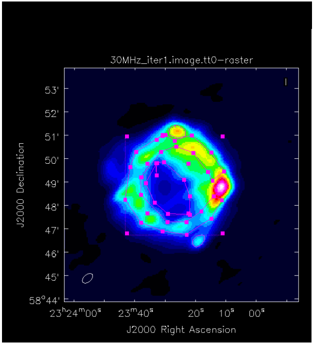
Free-free optical depth in the Rayleigh-Jeans approximation:

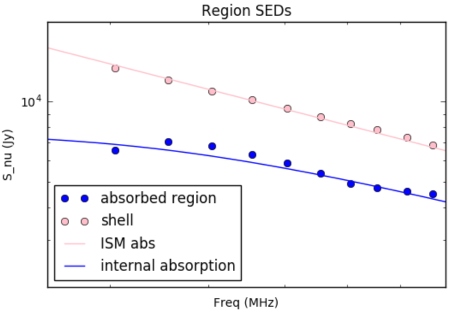
$$\tau_\nu = 3.014 \times 10^4\, Z \left(\frac{T}{\mathrm{K}}\right)^{-3/2} \left(\frac{\nu}{\mathrm{MHz}}\right)^{-2} \left(\frac{\mathrm{EM}}{\mathrm{pc\,cm^{-6}}}\right) g_{ff} \tag{3}$$

where Ze is the charge of the ion, $\mathrm{EM} = \int_0^{s'} n_e^2 ds'$ with n_e the number density of electrons, and g_{ff} is a Gaunt factor of order 1.

We fitted for the equation:

$$S_\nu = (S_{\nu,front} + S_{\nu,back}\, e^{-\tau_{\nu,int}})\, e^{-\tau_{\nu,ISM}} \tag{4}$$





The central, absorbed region is fit for free-free absorption from the unshocked ejecta. The parameters assumed for this plot are: $Z_{int} = 3$, $T_{int} = 300\text{K}$, and $S_{\nu,front} = S_{\nu,back}$. The best-fit emission measure is $\text{EM}_{int} = 1.44 \text{ pc cm}^{-6}$

Mass estimate

If $n_e \propto$ constant inside the reverse shock, then $\mathrm{EM} = n_e^2 l$. In this case, the mass in the unshocked ejecta is:

$$
\begin{aligned}
M &= A\, m_p \, \frac{1}{Z} \sqrt{\frac{\mathrm{EM}}{l}}\, V \\
&= 0.59\mathrm{M}_\odot \left(\frac{3}{\mathrm{Z}}\right) \left(\frac{\mathrm{EM}}{1.44\mathrm{pc\,cm^{-6}}}\right)^{1/2} \left(\frac{\mathrm{l}}{0.19\mathrm{pc}}\right)^{-1/2} \left(\frac{\mathrm{V}}{1.1\mathrm{pc}^3}\right)
\end{aligned}
\tag{5}
$$

Here A is the average mass number of the ions, and m_p is the mass of the proton.

The mass estimate is dependent on the assumed geometry of the ejecta.

Future work

- Understand the effect of internal absorption on the spectrum of Cas A; absorbed fraction f
- Effect on frequency dependence of the secular decline ???

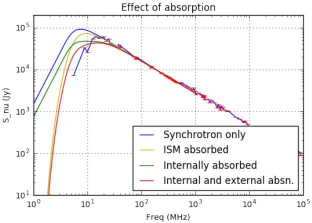


Figure: Effect of different absorption effects on the broadband radio spectrum of Cas A.