Investigating the Structure of the Cygnus Loop using Radio Wavelength Observations

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Goal:

The Cygnus Loop is an often-cited example of a supernova remnant given its large size and convenient location in the sky. However, it has an unusual structure for which there are two prevailing hypotheses: the more widely accepted viewpoint that it is the result of a blowout region into a low-density area or that it is two separate supernova remnants in close proximity. The goal for this project is to investigate the evidence supporting each possibility by analyzing the data received from the Galactic Arecibo L-band Feed Array Continuum Transit Survey (GALFACTS), the Dominion Radio Astrophysical Observatory (DRAO) and the Low Frequency Array (LOFAR). We hope to further understand its nature using both Rotation Measure and Spectral Index analyses of the northern and southern regions.

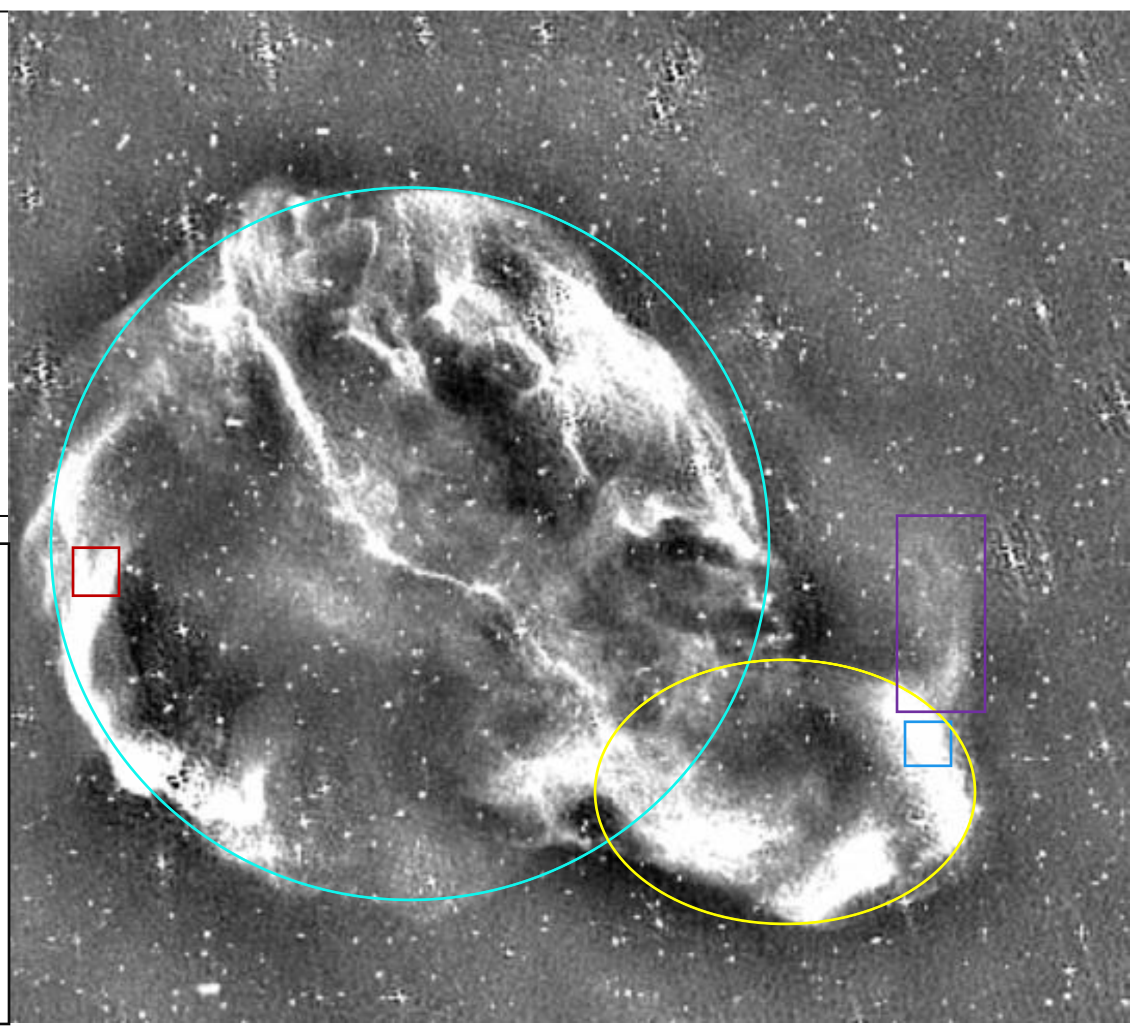
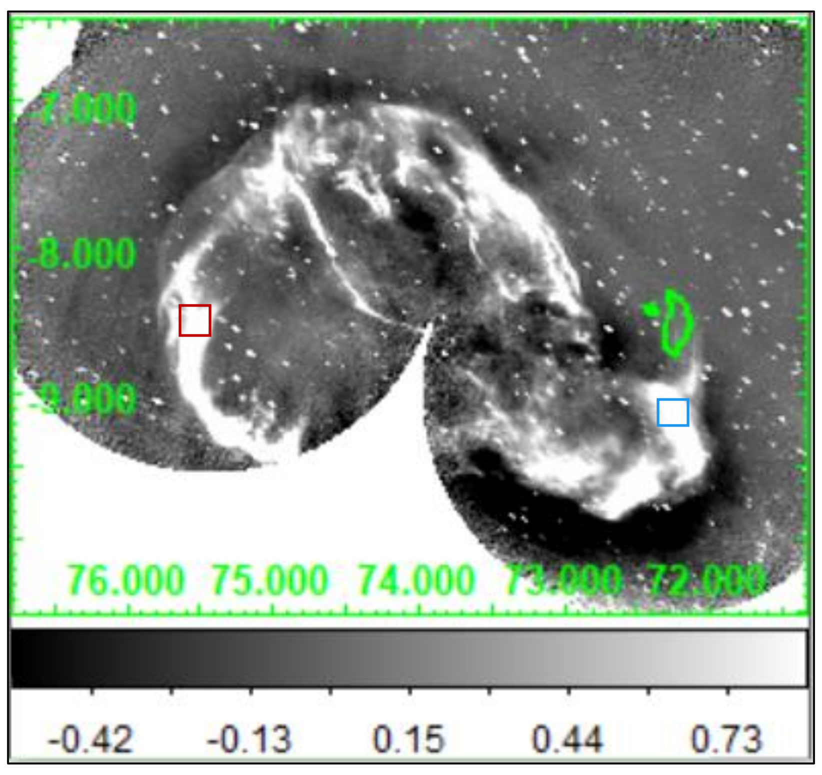


Figure 1: Diagram showing the Cygnus Loop, using the flux density measured by LOFAR at 143.65MHz. The northern region is represented by the cyan circle, whereas the southern region is shown in yellow. An extension from the south is outlined in purple. The blue and red boxes represent the regions sampled for the TT-plot.

Data:



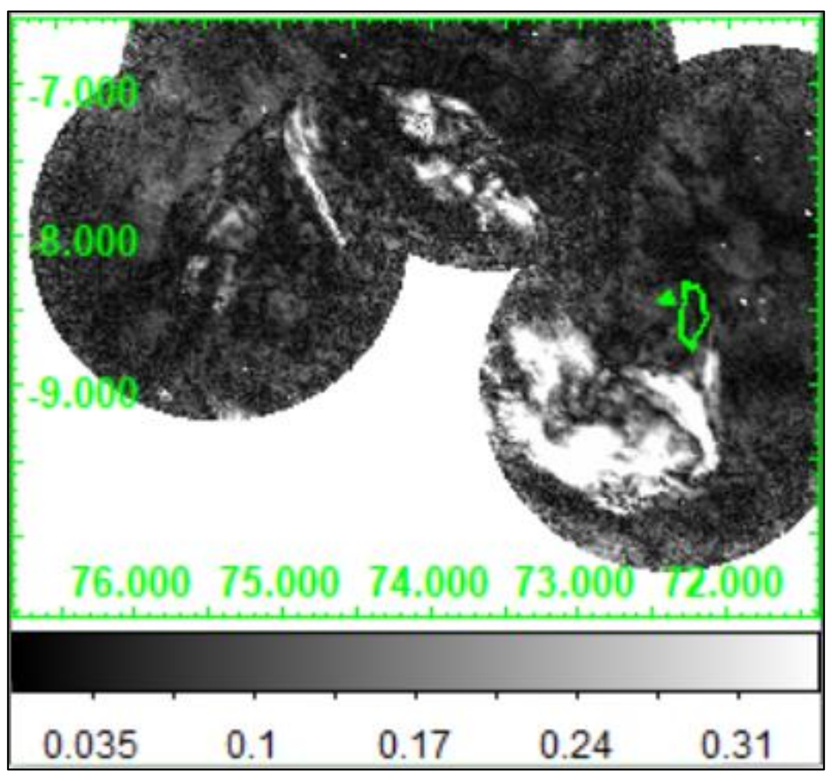


Figure 2: Total Intensity measured by DRAO at 1420MHz in units of Kelvin. Blue and red boxes indicate the regions taken for the TT-plot.
Figure 3: Polarized Intensity of DRAO data in units of Kelvin.
Coordinate axes represent Galactic Longitude (x-axis) and Latitude (y-axis).

The green contours in the figures to the left represent polarized emission as seen in the Faraday Depth Spectrum for LOFAR. We make special note of this because of how incredibly unusual it is to detect coherent polarization from synchrotron radiation at such low frequencies. As well, the feature shown in Figure 1 with the purple box has not yet been seen in other observations of the Cygnus Loop, potentially due to a combination of the higher resolution and lower frequencies.

Rotation Measure

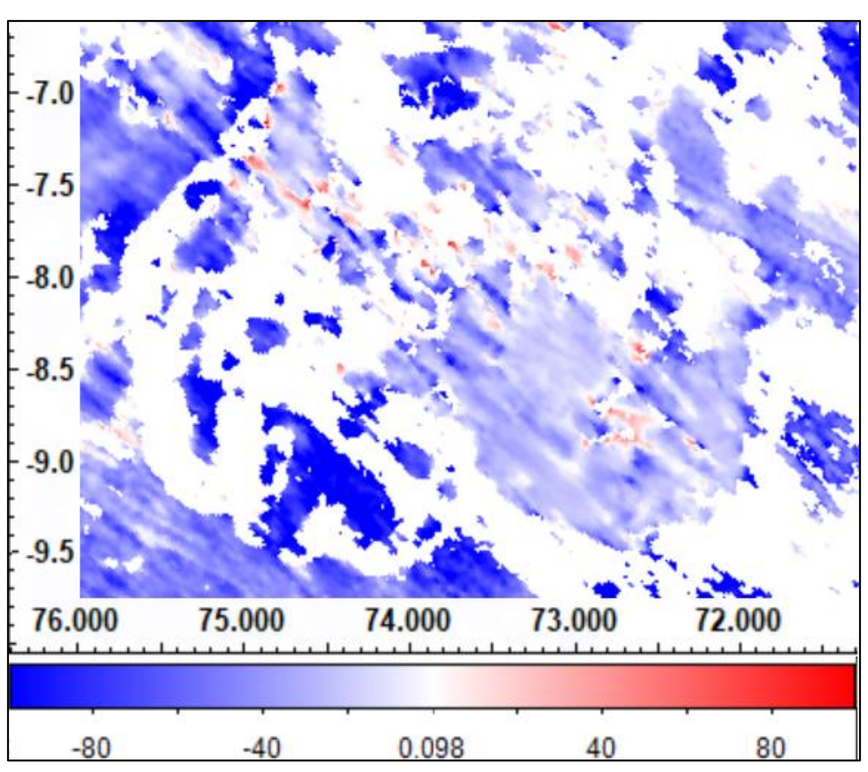
Background:

Polarized synchrotron emission, generated by relativistic electrons spiraling around magnetic field lines, is rotated via the Faraday Rotation effect as it propagates through a medium as a function of frequency. This is represented by the Rotation Measure (RM), proportional to the integral of the product of the electron density and the line-of-sight component of the magnetic field.

Method:

RM synthesis was performed using the Python package RM-Tools. Regions where the Polarized Intensity was below 0.06K were masked in the RM map to reduce the interference of artifacts and noise.

Data:



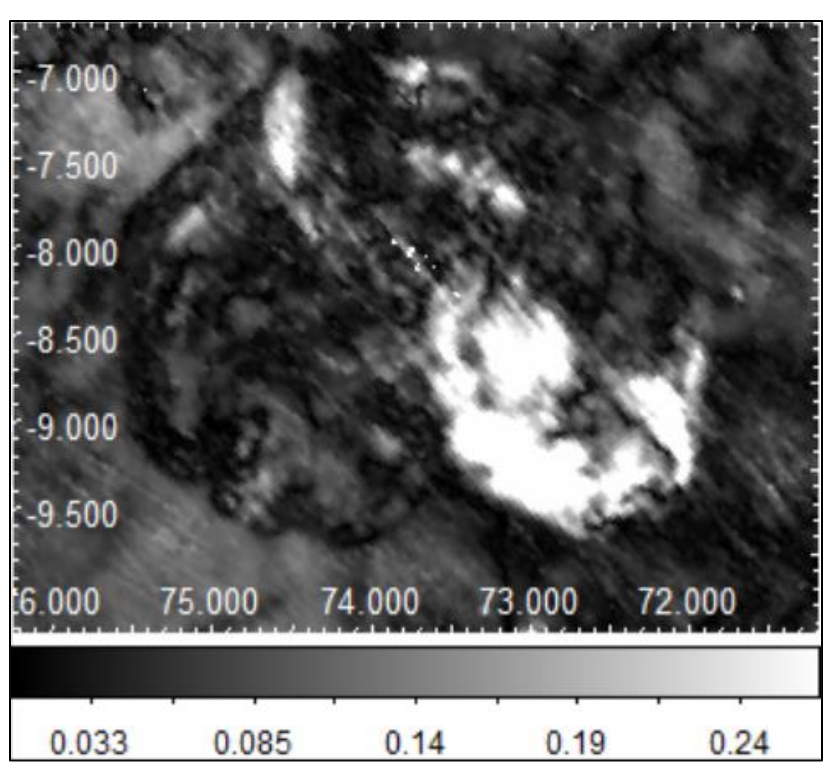


Figure 4: Rotation Measure map in units of rad/m^2 generated using GALFACTS data containing frequency range 1.37 - 1.52GHz.
Figure 5: Polarized Intensity of GALFACTS in units of Kelvin.
Coordinate axes represent Galactic Longitude (x-axis) and Latitude (y-axis).

Comments:

In Figure 1, the RM of the southern region is unusually uniform where one might expect variations due to the turbulence in the magnetic field. Another feature to note is the area of positive RM in the center of the southern region. In Figure 2, a substantial difference in polarized intensity between the two regions is clearly visible.

Spectral Index

Background:

The spectral index is the measure of how the flux density of an object changes with frequency, representing the distribution of the electron energies. This may indicate the age or energetic dynamics within the supernova remnant.

Method:

Background point sources interfering with the data were removed using the AegeanTools Package. The LOFAR data was convolved from a beam size of 6"x6" to 100"x50" to match the DRAO data. The data was converted from Jy/bm to Kelvin and the Montage program was used to match image sizes.

Temperature-Temperature (TT) plot:

$$\frac{T_1}{T_2} = \left(\frac{\nu_1}{\nu_2}\right)^{-\beta}$$

Using the relation on the right, the temperatures from each image are plotted and the spectral index (β) is calculated using the slope. The following TT-plot was generated from the regions as shown above:

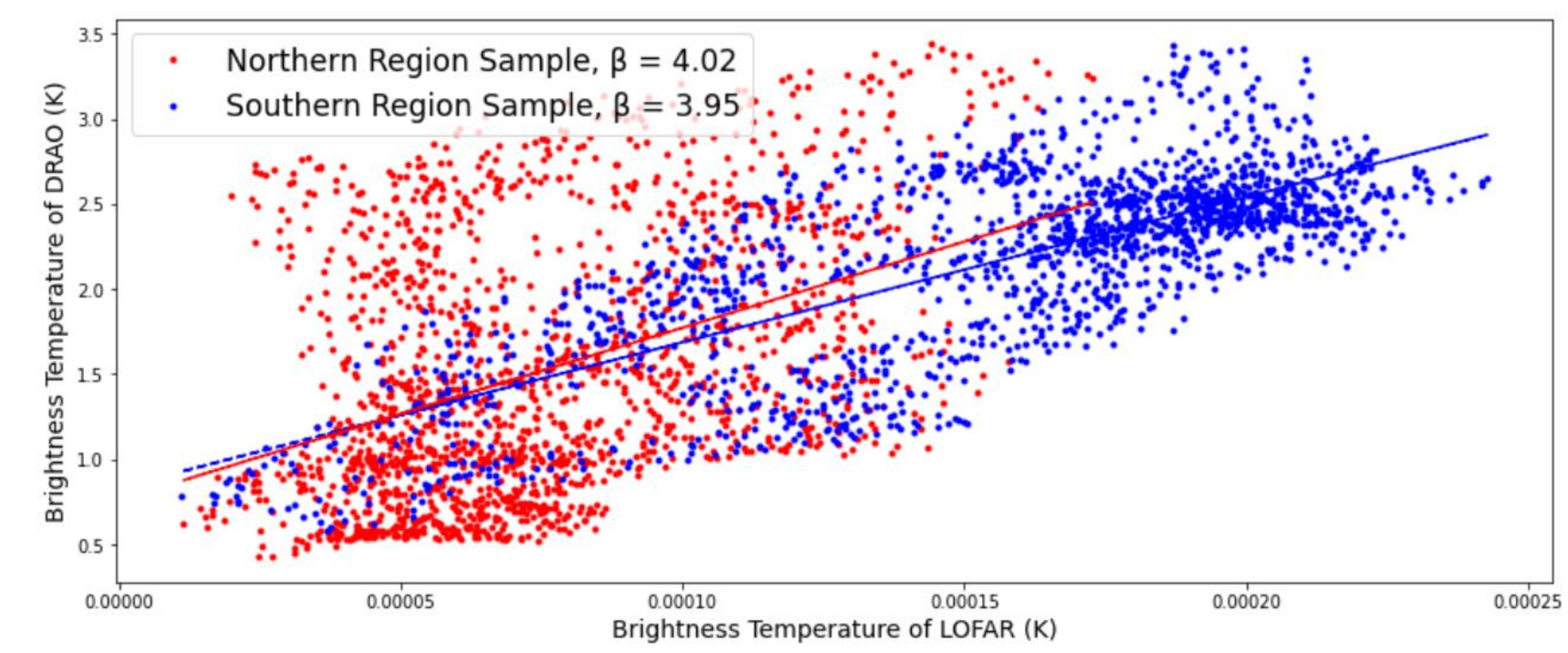


Figure 6: TT plot comparing the brightness temperature for LOFAR data against DRAO data for the two regions in Figures 1 and 2.

Comments:

The spectral index for the area sampled from the southern region is 3.95, which varies slightly from the value taken from the sample in the northern region, 4.02. This difference in spectrum between the two sections of the Cygnus Loop may be evidence in a difference in age or emission mechanisms. However, the values themselves do not match our expectations, based on measurements taken in previous work. This leads us to suspect an error in calibration or scaling. Despite this, the plots can still be compared relative to each other due to the error being systematic in nature.

Conclusion:

The new features found at these low frequencies may provide answers on the mechanisms and structure of a potential second supernova remnant within the Cygnus Loop. We would like to further analyze these features to compare to the overall structure. As well, further problem solving is required to identify and eliminate the error obtaining the spectral index. We would like to compare the spectral indices obtained here to literature values for datasets across other frequencies.

Acknowledgements:

I would like to acknowledge the contributions of Dr. Roland Kothes (Dominion Radio Astrophysical Observatory (DRAO) & National Research Council of Canada (NRC)), Dr. Samar Safi-Harb (University of Manitoba), as well as Dr. Cameron Van Eck (Dunlap Institute of Astronomy and Astrophysics). In addition, I would like to thank the University of Toronto and the SURP community for their invaluable support.