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The density and mass of unshocked ejecta in Cassiopeia A through low frequency radio absorption

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Abstract. Characterizing the ejecta in young SNRs is a requisite step towards a better understanding of stellar evolution. In Cassiopeia A the density and total mass remaining in the unshocked ejecta are important parameters for modeling its explosion and subsequent evolution. Low frequency (<100 MHz) radio observations of sufficient angular resolution offer a unique probe of unshocked ejecta revealed via free-free absorption against the synchrotron emitting shell. We have used the Very Large Array plus Pie Town Link extension to probe this cool, ionized absorber at 9$''$ and 18$''\!.5$ resolution at 74 MHz. Together with higher frequency data we estimate an electron density of 4.2 cm^{-3} and a total mass of 0.39 M$_\odot$ with uncertainties of a factor of ~2. This is a significant improvement over the 100 cm^{-3} upper limit offered by infrared [S III] line ratios from the *Spitzer Space Telescope*.

Keywords : shock waves, (ISM:) supernova remnants, ISM: individual: (Cassiopeia A), radio continuum: ISM, infrared: ISM

1. Introduction

In our extensive paper (DeLaney et al. 2014, in press) we provide a detailed analysis from the combination of radio and infrared observations to constrain the mass and density of unshocked ejecta interior to the reverse shock in the young supernova

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remnant Cassiopeia A. In this short proceedings paper we highlight our unique low frequency radio observations.

Cassiopeia A (Cas A) is the 2nd-youngest-known supernova remnant (SNR) in the Galaxy. With the discovery of light echoes from the explosion, we now know that Cas A resulted from a type IIb explosion (Krause et al. 2008). Cas A is one of the strongest synchrotron radio-emitting objects in the sky and has been observed extensively with the Very Large Array (VLA) since its commissioning in 1980.

The morphology of Cas A is complex with structure distributed over a variety of spatial scales. Here we concentrate on the relatively less well understood unchecked ejecta. These "unshocked ejecta" were discovered via absorption of low frequency (<100 MHz) radio emission (Kassim et al. 1995) and are also seen to radiate in the infrared in the emission lines of [O IV], [S III], [S IV], and [Si II] (Ennis et al. 2006). The term "unshocked" is somewhat of a misnomer because all of the ejecta were originally shocked by the passage of the blast wave through the star. However, the ejecta cooled during the subsequent expansion of the SNR. What we consider to be shocked ejecta today are those ejecta that have crossed through the reverse shock with the term "unshocked ejecta" referring to those ejecta that are still interior to the reverse shock. Thus the simple cartoon of Cas A's structure is that of cold ejecta in the interior of a roughly spherical shell composed of shocked gas that radiates strongly in multiple bands. At low frequencies, the radio emission from the far side of the shocked shell is absorbed by the cold, unshocked ejecta in the interior.

The absorption seen in the low frequency radio observations provides a means to probe the density and mass of the unshocked ejecta because the free-free optical depth (τ_ν) is related to emission measure and thus density. Kassim et al. (1995) attempted to determine the total mass of the unshocked ejecta, but due to using a τ_ν appropriate for a hydrogenic gas and a temperature that was too high, arrived at 19 $M_\odot$, which is unreasonably large considering that the total ejecta mass is likely only 2-4 $M_\odot$ (Hwang & Laming 2012). Given the role that the ejecta play in the evolution of SNRs, it is important to provide an accurate census of the total mass present, thus prompting a new look at the low frequency absorption analysis of Kassim et al. (1995).

2. Observations and data reduction

VLA radio observations from 74 MHz to 5 GHz are described extensively in DeLaney et al. (2014). A key point was to increase the spatial resolution of the lowest frequency images by utilizing the Pie Town (PT) link (hereafter called A+PT) with a maximum antenna separation of 72 km.

The observations at 330 MHz and 74 MHz were performed in spectral line mode due to the presence of narrow-band radio frequency interference (RFI). Images of Cygnus A at 330 MHz and 74 MHz, after normalization to the Baars et al. (1977)

absolute flux density scale, were used for both flux and bandpass calibration. Iterative cycling between self calibration and imaging was then used to improve the phase and gain solutions for Cas A and to derive the final images. Fortunately, as reviewed in DeLaney et al. (2014), Cas A so completely dominates the visibility phase measurements and its angular size is sufficiently small, that most of the complexities associated with low frequency synthesis imaging are avoided and not discussed here.

3. $9''$ 74 MHz and 330 MHz resolution images

Figure 1 shows the 2003 330 MHz and 74 MHz images at $9''$ resolution, which is the best resolution achieved with the A+PT link at 74 MHz. Clumpy structure is observed on a variety of spatial scales down to the resolution limit. Comparing to our $2\farcs5$ resolution PT link 330 MHz image (not shown here), it is clear that the same synchrotron features are responsible for the emission at 74 MHz. The right panel of Figure 1 is a plot of the angle-averaged radial surface brightness profiles of the 330 MHz and 74 MHz images normalized to their peak values. The emission in the center of the 74 MHz image is noticeably fainter than expected based on the appearance of the 330 MHz image, indicating the presence of thermal absorption at 74 MHz. This is corroborated by the detailed comparison of IR and radio data by DeLaney et al. (2014), with highlights discussed below.

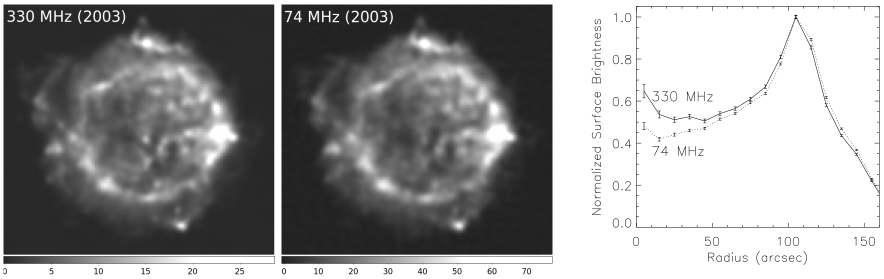

Figure 1. Left and center: 2003 A+PT configuration images of Cas A at 330 MHz and 74 MHz. The resolution is $9''$. Right: Normalized angle-averaged radial surface brightness profiles of the two images.

4. Comparison with infrared emission from unshocked ejecta

One of the most exciting discoveries with *Spitzer* was the presence of emission from unshocked ejecta in Cas A. This emission is most prominent in the lines of [O IV] and [Si II] (Ennis et al. 2006). The density and temperature conditions derived for this material based on the infrared line ratios confirms that it is indeed cold, low density, unshocked, photoionized ejecta (Smith et al. 2009). In order to confirm the hypothesis of Kassim et al. (1995) that the low frequency free-free absorption seen in Cas A

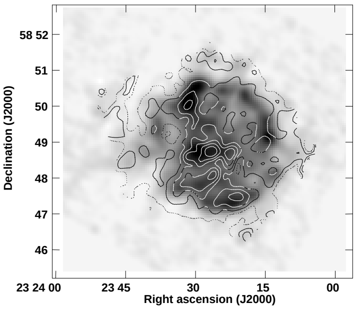

Figure 2. Thermal absorption (solid contours) with infrared [Si II] emission.

is due to unshocked ejecta, we compare the $\Delta\alpha$ (thermal absorption) image to the infrared [Si II] image. As shown in Figure 2, strong free-free absorption ($\Delta\alpha \gtrsim 0.1$) corresponds well to bright [Si II] emission ($\gtrsim 5 \times 10^{-7}$ W m^{-2} sr^{-1}).

There is not a one-to-one correlation between free-free absorption and [Si II] emission, nor should there be for a variety of considerations, including geometry. A full discussion is deferred to DeLaney et al. (2014).

5. Summary

Beyond the results reported in our abstract, we refer to DeLaney et al. (2014) for our extended conclusions. The promise of the emerging instruments is in expanding the population of SNRs, young and old, that can be probed for intrinsic and extrinsic thermal absorption and shock acceleration variations beyond pathologically bright sources like Cas A. More generally, the seemingly ubiquitous detection of resolved thermal absorption by the 74 MHz legacy VLA against the Galactic background (Nord et al. 2006) and towards, discrete non thermal sources (e.g. see Lacey et al. 2001; Brogan et al. 2005; Castelletti et al. 2007) confirms the phenomena will continue to emerge as a powerful tool for low frequency astrophysics.

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