Seeing Through the Interstellar Medium at Low Radio Frequencies

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ABSTRACT

Propagation effects due to the Galactic plasma have a strong frequency dependence and distort the wave front phase, as in scattering, or amplitude, as in free-free absorption. We discuss recent progress from the VLA and VLBA: (1) Cosmic ray tomography using opaque H II regions at 74 MHz; (2) Galactic supernova remnants at 74 MHz reveal extrinsic free-free absorption; and (3) Searches for anomalous interstellar scattering using 330 MHz VLBI. We consider future possibilities with the Low Frequency Array (LOFAR) and Square Kilometer Array (SKA).

INTRODUCTION

The Galaxy is filled with a dilute hydrogen plasma within which are localized, higher-density H II regions. Density fluctuations within these plasmas act to distort the phase of, i.e., scatter, a progagating radio wave, and, if the brightness temperature of the illuminating source is higher than the electron temperature within the plasma, these plasmas can distort the amplitude of, i.e., absorb, the propagating wave.

Both radio-wave scattering and thermal bremsstrahlung (free-free) absorption have a frequency dependence ν^{x} with $x \approx -2$. While their effects become significant below 100 MHz, even at higher frequencies these effects remain important. Over the majority of the operating frequency range of the Very Long Baseline Array (VLBA) and over a significant fraction of the frequency range of the Very Large Array (VLA), radio-wave scattering is detectable on some lines of sight through the Galaxy. This situation will remain unchanged for the Square Kilometer Array (SKA, planned frequency range 0.15–20 GHz). For the Low Frequency Array (LOFAR, planned frequency range 15–240 MHz), radio-wave scattering and free-free absorption may place fundamental limits on what can be observed.

These effects may be viewed in an ancipital light. The Galactic plasma and H II regions within it distort or obscure observations of background objects. Conversely, the detected signals contain a rich signal from either or both effects. Here we summarize a variety of on-going work that adopts the latter approach. We order the summary in order of decreasing optical depth, beginning with observations of optically-thick H II regions used to probe Galactic cosmic rays, observations of Galactic supernova remnants used to reveal translucent H II regions, and concluding with a search for anomalous interstellar scattering.

GALACTIC COSMIC RAY TOMOGRAPHY

The diffuse Galactic radio radiation at frequencies below 1000 MHz is due to synchrotron radiation from cosmic-ray electrons having energies of order 1 GeV spiralling in the Galactic magnetic field ($\sim$ 3 G). This relativistic gas has an energy density of order 1 eV cm^{-3}, comparable to that of other constituents of the interstellar medium (ISM). Yet the Galactic distribution and energy spectrum of these cosmic rays are determined relatively poorly in comparison to other constituents. Solar-wind modulation prevents the particles from reaching the Earth directly, so line-of-sight integrated measurements of the density and spectrum at both radio and gamma-ray wavelengths have been employed traditionally.

At low radio frequencies ($\nu < 100$ MHz), H II regions become opaque. With an interferometer, the flux density of an H II region is a direct measure of the quantity $T_e - T_{\mathrm{G,b}}$, where $T_e \approx 10^4$ K is the electron temperature of the H II region and $T_{\mathrm{G,b}}$ is the diffuse Galactic radio radiation temperature *behind* the H II region. At low radio frequencies, typically $T_{\mathrm{G,b}} > T_e$ so that the H II regions appear as "holes" in the image. If the distance to the H II region is known, the average cosmic-ray emissivity behind the H II region can be determined. Moreover, if the total emission along the line of sight is known also, say from a single-dish measurement, the average emissivity *in front* the H II region can be determined as well. By observing a large number of H II regions at different distances, the Galactic distribution of cosmic-ray emissivity can be determined. If multi-frequency observations are available, the spectrum can also be inferred.

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Determining the Galactic distribution of cosmic rays has been identified as a key science project of the Low Frequency Array (LOFAR). While this methodology has been employed before [1, 2, 3], these previous efforts have suffered because of the limited angular resolution and sensitivity of the low-frequency telescopes used. The higher angular resolution and sensitivity of LOFAR will allow H II regions anywhere in the Galaxy to be targetted.

Fig. 1 shows the H II region NGC 6357 in absorption [4], which we have obtained from an initial effort using the 74 MHz system on the D-configuration VLA to observe the Galactic center (a region with a high background temperature). The measured temperature of NGC 6357 is $-18\,000$ K, from which we determine $T_{\mathrm{G,b}} \approx 27\,000$ K at 74 MHz. For a typical path length through the Galaxy, we estimate a cosmic-ray emissivity $\epsilon_b \sim 3$ K pc^{-1}, comparable to previous estimates.

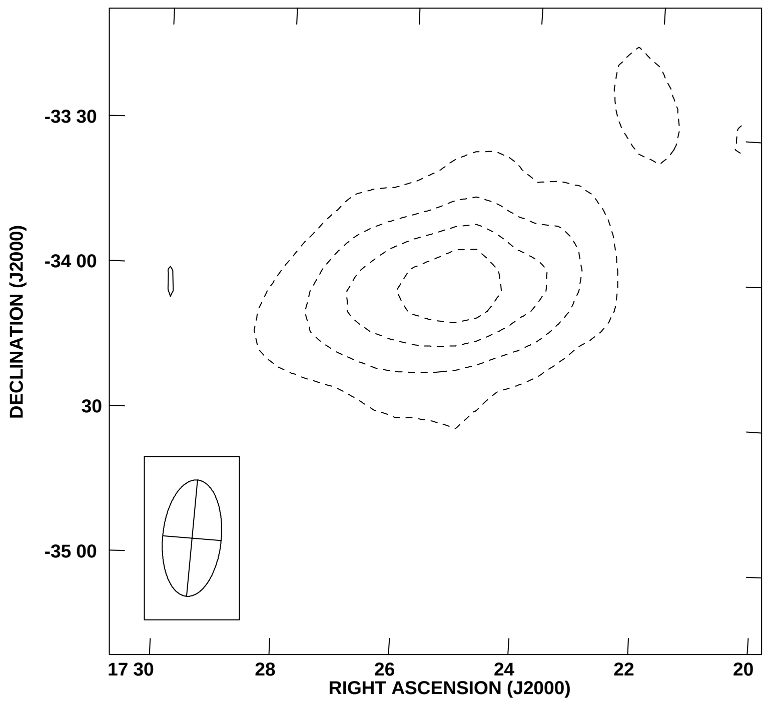

Figure 1: NGC 6357 as seen in absorption at 74 MHz. The rms noise level is 1.5 Jy beam^{-1}, and the contour levels are 1.5 Jy beam^{-1} $\times -20, -15, -10, -5$, 5, 10, 15, 20, and 40. The beam is $24' \times 12'$ and is shown in the lower left.

Our initial success simply in being able to detect this H II region, given the limited sensitivity of the 74 MHz VLA, has engendered a small 74 MHz survey of the Galactic plane. The 74 MHz VLA has a higher angular resolution than any previous low-frequency telescope, so in principle, it should enable us to penetrate deeper into the Galaxy. Between Galactic longitudes $-10^\circ \le \ell \le 30^\circ$, an initial census reveals nearly 10 additional H II regions seen in absorption. Future work will concentrate on determining ϵ_b, and possibly the foreground emissivity, toward these regions.

EXTRINSIC FREE-FREE ABSORPTION TOWARD GALACTIC SUPERNOVA REMNANTS

The integrated radio continuum spectra of Galactic supernova remnants (SNRs) are generally power-law from meter to centimeter wavelengths and shorter, with a continuum of spectral indices ranging from $\alpha \simeq -0.7$ ($S \propto \nu^{\alpha}$) for shell-type remnants to $\alpha \simeq -0.1$ for plerions. However, below 100 MHz, roughly two-thirds of SNRs show spectral turnovers indicative of thermal absorption [5, 6]. The inferred continuum optical depths and the poor correlation between the presence of a turnover and the distance to a SNR are inconsistent with absorption arising in the (globally-distributed) warm ionized medium ($n \sim 0.1$ cm^{-3}). Instead, the absorption must arise from localized ionized regions having an enhanced density ($n \gtrsim 1$ cm^{-3}) but of unknown scale size and with a small ($\le 1\%$) filling factor [6]. The favored interpretation has been that the absorbers represent extended H II region envelopes (EHEs), ionized gas surrounding normal H II regions, as postulated by [7] from comparison of centimeter- and meter-wavelength radio recombination line (RRL) observations. Alternatively, the absorption could be caused by the superposition of many small, normal H II regions or planetary nebulae along the line of site. Until now, low-frequency observations have had insufficient resolution to resolve spatially the morphology of the absorption and thereby constrain the geometry and scale size of the absorber.

The supernova remnant W49B (G43.3$-$0.2) is the nonthermal component of the W49 complex. It is a relatively young ($\sim$ 3000 yr), bright, and extended ($\approx 5'$) shell-type SNR, whose integrated spectrum also shows a low-frequency turnover with a free-free 30.9 MHz optical depth of $\tau_{30.9} = 0.9 \pm 0.3$ [5, 6]. Low resolution detection of RRLs in the direction of W49B, unusual for a Galactic SNR, provide further strong evidence for ionized gas along the line of sight [8].

We obtained sub-arcminute resolution imaging of W49B at 74 MHz ($25''$, Fig. 2*a*) and 327 MHz ($6''$, Fig. 2*b*), the former being the lowest frequency at which the source has been resolved [9]. While the 327 MHz image shows a shell-like morphology similar to that at higher frequencies, the 74 MHz image differs considerably, with the southwest region of the remnant attenuated almost completely. The implied 74 MHz optical depth ($\approx$ 1.6) is much higher than the intrinsic absorption levels seen inside two other relatively young remnants nor are natural variations in the relativistic electron energy spectra expected at such levels. The geometry of the absorption is also inconsistent with intrinsic absorption.

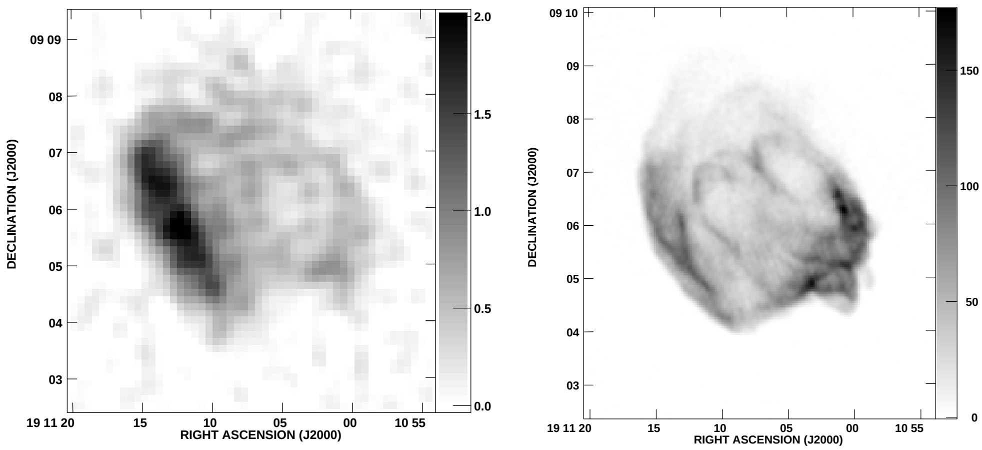

Figure 2: (*a*) The supernova remnant W49B at 74 MHz. The gray scale flux range is linear between 0 and 2 Jy beam $^{-1}$. (*b*) The supernova remnant W49B at 327 MHz. The sub-milliJansky sensitivity of this image makes it one of the highest dynamic range, low-frequency images ever obtained. The gray scale flux range is linear between 0 and 175 Jy beam $^{-1}$.

We attribute the absorption to extrinsic free-free absorption by a intervening cloud of thermal electrons. Its presence has already been inferred from the low-frequency turnover in the integrated continuum spectrum and from the detection of radio recombination lines toward the remnant. Our observations confirm the basic conclusions of those measurements, and our observations have resolved the absorber into a complex of classical H II regions surrounded either partially or fully by low-density H II gas. We identify this low-density gas as an extended H II region envelope (EHE) a few arcminutes in size (10 pc at 10 kpc), in good agreement with previous estimates from low resolution meter- and centimeter-wavelength recombination line observations [8]. Comparison of our radio images with H I and H_2CO observations also show that the intervening thermal gas is likely associated with neutral and molecular material as well.

ANOMALOUS INTERSTELLAR SCATTERING

Images of scattered radio sources and distorted pulses due to multi-path propagation from pulsars provide some of the most-used observables for probing microstructure ($\ll$ 1 pc) in the interstellar plasma. These observables are used to probe the amplitude of scattering and also, through the frequency scaling, to constrain the shape of the wavenumber spectrum for the microstructure. Inversion of scattering observables into information about the microstructure almost invariably relies on the assumption that the scattering strength is uniform in directions transverse to the line of sight.

Over the last decade, interstellar scattering measurements have revealed asymmetries in the scattered images of radio sources, [10, 11, 12]. These are interpreted most often in terms of anisotropy of the density microstructure that diffract the radiation. That anisotropy, in turn, is thought to reflect the orientation of magnetic fields in the plasma.

We have reconsiderd the the assumption of uniformity transverse to the line of sight in the analysis of angular and temporal broadening [13]. One reason is that the ISM shows structures on a wide variety of scales and so it is unreasonable to expect the scattering to be uniform across all lines of sight. Secondly, the physics that underlies asymmetric images is quite different if the asymmetry occurs on scales larger than diffractive scales. Thirdly, observations of the Crab pulsar show anomalous scalings of pulse broadening with frequency, which may indicate that scattering occurs within the pulsar magnetosphere rather than in a cold plasma [14].

Allowing for a scattering screen with an arbitrary spatial variation of scattering strength transverse to the line of sight, e.g., a disk or filaments, produces a number of consequences: (1) Source image shapes, such as image elongations and orientations, are determined by the physical extent of the screen rather than by the shapes of much-smaller diffracting microirregularities; (2) The variation with frequency of angular broadening is much weaker than the trademark ν^{-2} scaling law, including frequency-independent cases; and (3) Similar departure of the pulse broadening time from the expected ν^{-4} scaling occurs.

Some of these effects may have already been detected such as the possibility of scattering of pulses from the Crab pulsar by filaments in the Crab Nebula and image asymmetries from Galactic scattering of the sources Cyg X-3, Sgr A*, and NGC 6334B. A particularly promising opportunity to detect this anomalous scattering is from intervening spiral galaxies along the line of sight to compact active galactic nuclei. We have begun a 330 and 610 MHz observing program on the VLBA to detect such scattering. We also expect that future observations with LOFAR will be affected strongly by the structure of the scattering material.

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