Low frequency studies of the Galactic Centre with GMRT

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Abstract. We have observed the GC region at 255 and 154 MHz with the GMRT. From the 255 MHz map we detect 28 compact sources, and an anti-correlation of their deconvolved sizes with angular distance from the GC is observed. This is the first direct indication of scatter broadening for a statistically large sample of extragalactic sources in the region and we discuss its implications in determining the properties of the screen. Our multifrequency observations at 255 and 154 MHz in tandem with previous observations of the GC shows that the 7′ halo in Sgr A complex is a non-thermal source rather than a mixture of thermal and non-thermal electrons as was proposed before.

1. Introduction

The central region of the Galaxy is characterised by dense and turbulent environment not seen elsewhere in the Galaxy. A large number density of stars causes a good fraction of gas in the region to ionise which scatters any incident electromagnetic wavefront. Consequently the central source Sgr A* appears scatter broadened in radio frequencies to an extent not seen elsewhere for any sources of Galactic origin at the same frequency. Scatter broadening of similar magnitudes are also observed towards maser sources in the region \cite{1}. This raises the question on the location and properties of this screen. Earlier work \cite{1} suggested the screen to be at a distance of $\sim$kpc from the GC, but \cite{2} suggested a ‘hyperstrong scattering region’ within 0.5° from the GC which is located at a distance of $\sim$133 pc from it. However, there is no direct estimate of its distance from GC and \cite{3} discovered a source G359.87+0.18 seen through the scattering screen of \cite{2}, but scattered almost an order of magnitude less than their model. If extragalactic sources are observed through this region then it can be shown that

$$\theta_{xgal} = \frac{D_{GC}}{\Delta_{GC}} \theta_{Gal}$$  \hspace{1cm} (1)

\cite{1}, where $\theta_{xgal}$ is the characteristic diameter of an extragalactic source, $D_{GC}$ is the distance to Sun from the GC, $\Delta_{GC}$ is the distance to the scattering screen from GC and $\theta_{Gal}$ is the characteristic diameter of a Galactic source. The above equation can be used to determine the distance to the screen from the GC. Scattering is proportional to the square of wavelengths and extrapolation of measured scattering diameter of a few extragalactic sources a few degrees away from GC \cite{4} to lower frequencies indicates a scattering size comparable to the synthesised beam size at 250 MHz of GMRT, which can be measured.
Being located in the central few arc minute of the Galaxy, Sgr A complex has attracted our attention for many decades. This complex from larger to smaller scale is essentially composed of 4 separate objects:

(i) The 7′ halo, which is modelled as a mixture of thermal and non-thermal electrons [6].
(ii) Sgr A East, which is a supernova remnant (SNR).
(iii) Sgr A West, which is a HII region and being located closer than Sgr A East, absorbs its emission through free-free absorption at low radio frequencies [6].
(iv) Sgr A*, which is coincident with the supermassive black hole at the Galactic Centre and is found to be located in front of Sgr A West [5]. The emission from Sgr A East, Sgr A West and Sgr A* is believed to be non-thermal, thermal and non-thermal respectively.

The high frequency spectral index of Sgr A East is \( \sim -1 \) \( (S(\nu) \propto \nu^\alpha) \), but its flux density at 330 MHz is only about 1.5 higher than what is measured at 1.4 GHz. In order to explain this anomaly, [6] proposed the 7′ halo to be a mixture of thermal and non-thermal electrons, and estimated its optical depth at 330 MHz to be \( \sim 1 \). However, they suggested it on the basis of observations done at only 2 different frequencies (1.4 GHz and 330 MHz), but free-free absorption has at least 2 free parameters. So, their model of 7′ halo remains highly questionable and observations at frequencies lower than 330 MHz will better constrain any free-free absorption by 7′ halo.

In order to measure the properties of ionised gas at the GC through scatter broadening and to determine the nature of 7′ halo through low frequency observations, we have observed this region with high angular resolution at 255 and 154 MHz with GMRT and our tentative results are presented here.

2. Observations and data reductions

Observation of the Galactic Centre region at 255 MHz was carried out on 13th March 2003, and the 154 MHz observation was done on 20th August 2005. To reduce radio frequency interference (RFI) on the data, a narrow IF bandwidth of 6 MHz having relatively less RFI was chosen for observations at 255 and 154 MHz (other steps like employing 14 db Solar attenuator at the preamplifier stage was also taken to minimise amplifier saturation in presence of strong RFI). Absolute flux density calibration was performed using 3C48. 1830-36 and 1714-252 were used as secondary calibrators. In the absence of System temperature measurements, we have performed gain calibration following [5] with automatic level control (ALC) off. After calibration and editing, a pseudo-continuum data base was made to avoid bandwidth smearing within the primary beam. The initial images were improved by phase-only self-calibration (self-cal).

3. Results & Discussions

3.1. Scatter broadening of extragalactic sources at 255 MHz

To detect small diameter sources in the region, we first made a map of Sgr A complex with all the data and subtracted the Fourier transform of its Clean components from the data and re-imaged with a short UV cutoff to resolve out any extended emission of size larger than 7′. The synthesised beam size of the resulted map is 17.3′′ × 12.5′′. A total of 28 small diameter sources are detected and Fig. 1 shows a plot of source size as a function of Galactic longitude and latitude. In the plot, X-axis errorbars indicate the average half-width of the synthesised beam, and Y-axis errorbars indicate the deconvolved average (by averaging the major and minor axis sizes) size of the sources. To make the symbols visible, actual angular scales measured in source sizes and synthesised beam have been multiplied by a factor of 30 in these plots. As can be seen from the plot, source sizes appear to increase near the GC. To investigate a possible correlation of a decrease of source size as a function of distance from GC, we plot in Fig. 2 source sizes as a function of angular distance from GC. Since we are measuring scattering diameter of extragalactic sources, we have removed 2 possible Galactic sources from the sample before plotting. A good fraction fraction of the remaining 26 sources are shown to be extragalactic from their spectral index and morphology [7]. Sources which are not observed in [7] have counterparts.
in 1.4 GHZ VLA Galactic plane survey ([10], [11]) and have a steep spectral index in the range expected for extragalactic sources. From the data plotted, Spearman rank correlation of decreasing source size with angular distance from GC is estimated to be 0.54, which makes the correlation valid at 99% confidence level. Since intrinsic sizes of extragalactic sources are independent of angular separation from GC, this correlation establishes GC contribution in causing the scatter broadening of sources. The scattering diameter of these sources extrapolated close to GC at 255 MHz is about 25\(^{\prime\prime}\). This is at least a factor of 6 smaller as compared to what is expected from [2].

The scattering diameter measured for small diameter sources in our map is comparable to what is expected from VLBA observations of extragalactic sources a few degrees away from GC[4]. The scattering screen we detect produce scatter broadening within a factor of two of what is expected for maser sources in the GC region extrapolated to this frequency. Following Equation (1), if this scattering screen is uniformly distributed, it is located \(\geq 4\) kpc away from the GC. A circularly symmetric screen around the GC at this distance will produce perceptible effects even 10 degrees away from GC along the Galactic plane. However, Fig. 2 shows the extent of this screen from GC to be only \(\sim 1^{\circ}\), which shows the screen is not symmetrically distributed around the rotation axis of the Galaxy and could be just a line of sight ionised cloud.

Other than G359.87+0.18, we have also detected one source G359.6+0.3 (Fig. 3) [7] which is a FRII radio galaxy and is located within the hyperstrong scattering regime [2], but is scatter broadened almost a factor of ten less than the hyperstrong scattering regime. Consequently, if the hyperstrong scattering medium exists, it ought to have a small filling factor, so that all the above extragalactic sources are not seen through it. We note that the maser sources could be preferentially located in the clouds, ionised surfaces of which could be responsible for producing any possible hyperstrong scattering. However, extragalactic sources are seen randomly and unless both Galactic and extragalactic sources are seen through the same cloud, comparison of scattering diameters of Galactic vs. extragalactic sources to find the distance of the screen from GC may not be correct.

**Figure 1.** Plot of source size as a function of Galactic longitude and latitude. X-axis errorbars indicate the average half-width of the synthesised beam, and Y-axis errorbars indicate the deconvolved average size of the sources. Source sizes and synthesised beam size have been multiplied by a factor of 30 in this plot.

**Figure 2.** Plot of source size as a function of distance from GC.
3.2. 7′ halo and Sgr A East at low radio frequencies

A false colour image of GC at 154 MHz is shown in Fig. 4, which is the highest sensitivity, high resolution image of the region below 330 MHz, and shows the presence of several known sources Sgr A East, Radio arc, Sgr C filament and SNR G0.33+0.0. To model the emission properties of sources in the Sgr A complex, we measure the total flux densities of 7′ halo, Sgr A East, Sgr A West at frequencies of 1.4 GHz, 620, 320, 255 and 154 MHz following the procedure given in [5]. Fig. 5 shows the plot of flux density as a function of frequency for Sgr A East, and Fig. 6 shows the same for 7′ halo. The low frequency turnover of both these objects occur at similar frequencies and they appear absorbed to almost the same extent at 154 MHz suggesting absorption extrinsic to these sources, possibly by a line of sight diffuse ionised gas. To quantitatively verify this, we assume free-free absorption of synchrotron emission emitted from Sgr A East and 7′ halo and plot the fit of the following equation (solid curve) to the data in Figs. 5 & 6 respectively.

\[
S = S_0 \times \nu^\alpha \times \exp(-\tau)
\]

\[
\tau = 0.2 \times n_e^2 \times \nu^{-2.1} T_e^{-1.35}
\]

where \( S \) is the measured flux density at a frequency of \( \nu \) GHz, \( \tau \) is the free-free optical depth at that frequency, \( S_0 \) is the flux density of the background source at 1 GHz, and \( \alpha \) is the synchrotron spectral index. From the fit, we estimate for Sgr A East \( \alpha=-0.5\pm0.2 \), and the absorbing screen has \( n_e^2 \times T_e^{-1.35}=0.23\pm0.025 \). For 7′ halo we estimate \( \alpha=-0.27\pm0.2 \), and the absorbing screen has \( n_e^2 \times T_e^{-1.35}=0.18\pm0.05 \). It shows the free-free absorption caused by the screen is the same within the measurement errors towards both Sgr A East and 7′ halo at any frequency. Therefore, line of sight absorption by a single foreground screen can adequately explain the observed emission properties of both the sources. 7′ halo can simply be modelled as a synchrotron source, which is contrary to what was proposed by [6]. We note the synchrotron spectral index of both the sources between 1.4 GHz and 154 MHz is significantly flatter than what is estimated from higher frequencies [6], and the change in their spectral index is \( \leq 0.5 \). This indicates that there is a break in the synchrotron spectrum at frequencies around 1.4 GHz for these objects. If the magnetic field in Sgr A East is taken to be 3.5 mG [8], then following [9], estimated age of Sgr A East is about 10^4 years. If the magnetic field in 7′ halo is assumed to be the same as in Sgr A East, its age will also be the same.

4. Conclusions

We have observed the GC region at 255 and 154 MHz with the GMRT. From the 255 MHz map we detect 28 compact sources, and an anti-correlation of their deconvolved sizes with angular distance from the GC is observed. This shows scatter broadening due to GC ionised medium. If this medium is homogeneous, it is located at least 4 kpc away from the GC. However, it appears more likely that the ionised medium is clumpy and a good fraction of extragalactic sources are not seen through the clumpy screen, where the maser sources are preferentially located. Our multifrequency observations at 255 and 154 MHz in tandem with previous observations of the GC shows that the 7′ halo in Sgr A complex is a non-thermal source rather than a mixture of thermal and non-thermal electrons as was proposed before.

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Figure 3. A 5 GHz VLA map of the FRII galaxy G359.6+0.3

Figure 4. Central 1 degree region of the Galaxy at 154 MHz. Resolution $\sim 45''$, rms noise is about 25 mJy/Beam.

Figure 5. Plot of flux density of Sgr A East between 1.5 and 0.15 GHz

Figure 6. Plot of flux density of $7'$ halo between 1.5 and 0.15 GHz

References
[1] van Langevelde, H. J., Frail, D. A., Cordes, J. M., & Diamond, P. J. 1992 ApJ 396 686
[2] Lazio, T. J. W. & Cordes, J. M. 1998 ApJS 118 201
[3] Lazio, T. J. W., Anantharamaiah, K. R., Goss, W. M., Kassim, N. E., & Cordes, J. M. 1999 ApJ 515 196
[4] Bower, G. C., Backer, D. C., & Sramek, R. A. 2001 ApJ 558 127
[5] Roy, S. & Rao, A.P. 2004 MNRAS 349 L25
[6] Pedlar, A., Anantharamaiah, K. R., Ekers, R. D., et al. 1989 ApJ 342 769
[7] Roy, S., Rao A. P. & Subrahmanyan R. 2005 MNRAS 360 1305
[8] Yusef-Zadeh, F. 1999 ApJ 512 230
[9] Kardashev, N. S. 1962 Soviet Astronomy 6 317
[10] Zoonematkermani, S., Helfand, D. J., Becker, R. H., White, R. L., & Perley, R. A. 1990 ApJS 74 181
[11] Helfand, D. J., Zoonematkermani, S., Becker, R. H., & White, R. L. 1992 ApJS 80 211