Characterization of unresolved and unclassified sources detected in radio continuum surveys of the Galactic plane


1 Discipline of Astronomy, Astrophysics and Space Engineering, Indian Institute of Technology Indore, Indore 453552, India
2 Department of Physics, Indian Institute of Science, Bangalore 560012, India
3 Max Planck Institute for Astronomy, K"{a}nigstuhl 17, 69117 Heidelberg, Germany
4 Max-Planck-Institut f"{u}r Radioastronomie, Auf dem H"{o}g 69, 53121 Bonn, Germany
5 Centre for Astrophysics and Planetary Science, University of Kent, Canterbury, CT2 7NH, UK

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ABSTRACT
The continuum emission from 1 to 2 GHz of The HI/OH/Recombination line survey of the inner Milky Way (THOR) at $\lesssim 18''$ resolution covers $\sim 132$ square degrees of the Galactic plane and detects 10387 sources. Similarly, the first data release of the Global View of Star Formation in the Milky Way (GLOSTAR) surveys covers $\sim 16$ square degrees of the Galactic plane from 4-8 GHz at $18''$ resolution and detects 1575 sources. However, a large fraction of the unresolved discrete sources detected in these radio continuum surveys of the Galactic plane remain unclassified. Here, we study the Euclidean-normalized differential source counts of unclassified and unresolved sources detected in these surveys and compare them with simulated extragalactic radio source populations as well as previously established source counts. We find that the differential source counts for THOR and GLOSTAR surveys are in excellent agreement with both simulation and previous observations. We also estimate the angular two-point correlation function of unclassified and unresolved sources detected in THOR survey. We find a higher clustering amplitude in comparison with the Faint Images of the Radio Sky at Twenty-cm (FIRST) survey up to the angular separation of $5^\circ$. The decrease in angular correlation with increasing flux cut and the excellent agreement of clustering pattern of sources above 1 mJy with high $z$ samples ($z > 0.5$) of the FIRST survey indicates that these sources might be high $z$ extragalactic compact objects. The similar pattern of one-point and two-point statistics of unclassified and compact sources with extragalactic surveys and simulations confirms the extragalactic origin of these sources.

Key words: radio continuum: general – galaxies – surveys

1 INTRODUCTION
Continuum surveys of the Galactic plane at radio wavelength are an excellent way to study different source populations such as HII regions, planetary nebulae (PNe), radio stars etc (Bihr et al. 2016; Beuther et al. 2016). These surveys also help to understand different physical processes in the interstellar medium. There are several high-resolution surveys of the Galactic plane from near-infrared to mm wavelengths but only a few at radio wavelength (see Beuther et al. 2016 and references therein). The HI/OH/Recombination line survey of the inner Milky Way (THOR) and the Global View of Star Formation in the Milky Way (GLOSTAR) are two such surveys of the Galactic plane at radio wavelengths in high-resolution with unprecedented sensitivity.

THOR covers a large fraction of the first Galactic quadrant with the extended Karl G. Jansky Very Large Array (VLA) in C-configuration at L-band from 1 to 2 GHz and detects 10387 sources (Beuther et al. 2016; Wang et al. 2018). Wang et al. (2018) have classified a subset of these sources as HII regions, pulsars, X-ray sources, planetary nebulae, supernova remnants and extragalactic jets after comparing with multi-frequency catalogues. GLOSTAR covers the Galactic plane between $-2^\circ < l < 60^\circ$ and $|b| < 1^\circ$, and then Cygnus X region from $76^\circ < l < 83^\circ$ and $-1^\circ < b < 2^\circ$ with the VLA in D- and B-configuration at C-band from 4 to 8 GHz.
Medina et al. (2019) have analyzed a portion of the D-array data and published the first source catalogue consisting of 1575 sources. They have also identified the sources in the GLOSTAR survey by cross-correlating with different catalogues. However, a large number of sources remain unclassified in both surveys. Wang et al. (2018) have found that the unclassified sources and identified Galactic sources show different spatial and spectral index distributions. The Galactic sources are more concentrated in low longitude region and near the Galactic mid-plane. Also, the spectral index distribution shows a peak around $\alpha \sim -1$ for unclassified sources in comparison with Galactic sources. However, they have also found a significant number of unclassified sources with $\alpha \geq 0$ (Wang et al. 2018). Medina et al. (2019) have also found a similar distinctive behavior in spatial and spectral index distributions. The Galactic unclassified sources and identified Galactic sources show different spatial and spectral index distributions. The Galactic mid-plane. Also, the spectral index distribution shows a peak around $\alpha \sim -1$ for unclassified sources in comparison with Galactic sources. However, they have also found a significant number of unclassified sources with $\alpha \geq 0$ (Wang et al. 2018).

Out of these unclassified sources, 7800 (75%) sources are unclassified too. Similar to THOR, we have only analyzed the statistical properties of these unresolved and unclassified sources.

### 3 Differential Source Counts

There are extensive study of source counts as a function of flux density at high frequency as well as at low frequency. It is well established that Euclidean-normalized differential source counts at 1.4 GHz show a flattening at $\sim 1$ mJy corresponding to a rise in the source population of star-forming galaxies (SFGs) and radio-quiet AGNs (see de Zotti et al. 2010 for a detail review). We have estimated the Euclidean-normalized differential source counts of unresolved and unclassified sources detected in THOR and GLOSTAR survey and compared our findings with previous observations. We have binned the integrated flux density of sources in logarithmic space and adjusted the bins in such a way that the highest flux density bin includes a minimum of 3 sources. The raw source counts (N) in each bin are corrected for image area detection fraction or the visibility area. We have estimated the fraction of area (f) over which a source with a given flux density can be detected (its visibility area) and weighted the raw source counts by the reciprocal of that fraction (Windhorst et al. 1985). The corrected source counts ($N_c = N/f$) were then divided by the total image area (Ω in steradians) and bin width (ΔS in Jy). This gives the differential source counts as a function of flux density. We have normalized the differential source count distribution to Euclidean geometry by multiplying it with $S^{2.5}$, where $S$ is the mean flux density of sources in each bin (Windhorst et al. 1985).

THOR catalogue is 94% complete above 7σ (Bühr et al. 2016; Wang et al. 2018), whereas, GLOSTAR catalogue is 95% complete above 7σ threshold (Medina et al. 2019).
7σ and hence no completeness correction was applied to the differential source counts. Resolution bias causes for underestimation of source counts of extended sources in peak flux density selection during source extraction. However, both surveys checked the resolved sources visually and categorized those separately in the final catalogue. We only use the unresolved/compact sources in this analysis, and hence, this bias is not an issue here. Eddington bias is significant near the detection threshold (5σ for these catalogues) due to steep source counts at low flux densities and the fact that this bias redistributes low flux density sources to high flux bins. However, the differential source counts will not be affected by this bias due to the imposed high flux cut (>7σ) in this analysis. Any false detection of observational sidelobe artifacts as real sources will boost the source counts. However, both surveys identified these artifacts by visual inspection of all sources and excluded those from the final catalogue (Wang et al. 2018; Medina et al. 2019).

The Euclidean-normalized differential source counts for THOR and GLOSTAR catalogues are shown in Fig. 1, where the error bars are Poissonian. In the left panel of Fig. 1, we compare our findings with two simulated catalogues, the SKA Design Study simulations (SKADS, Wilman et al. 2008) and the Tiered Extragalactic Continuum Simulations (T-RECS, Bonaldi et al. 2019). The SKADS catalogue spans an area of 100 deg² with a minimum flux density of 1 μJy at 1.4 GHz and also includes four distinct source types: Fanaroff-Riley Class I (FRI) and Class II (FRII), radio-quiet AGNs (RQQ) and star-forming galaxies (SFGs). The source counts of SFGs, AGNs and RQQ taken from SKADS catalogue are also shown. There are three different settings available in T-RECS simulation for the two main radio source populations: AGNs and SFGs. We choose the ‘medium’ T-RECS catalogue, which covers 25 deg² with a minimum flux density of 10 nJy at 1.4 GHz and also incorporates the effect of clustering in their simulation (Bonaldi et al. 2019). The population of AGNs and SFGs in T-RECS simulation are also shown in Fig. 1.

Along with simulated radio catalogues we have also compared differential source counts with observed source populations at low-frequency as well as high-frequency in the right panel of Fig. 1. The differential source counts from other observations include: the TIFR GMRT Sky Survey at 150 MHz (TGSS-ADR1; Intema et al. 2017), GaLactic and Extragalactic All-sky MWA survey at 154 MHz (GLEAM; Franzen et al. 2019), BOOTES field at 150 MHz using LOFAR (Williams et al. 2016), Super-CLASS supercluster at 325 MHz with the GMRT (Riseley et al. 2016), ELIAS-N1 field at 400 MHz using uGMRT (Chakhovski et al. 2019), Lockman hole field at 1.4 GHz with the LOFAR (Prandoni et al. 2019), the 1.4 GHz source counts based on observation with VLA by Condon (1984), the Phoenix Deep Survey at 1.4 GHz with ATCA (Hopkins et al. 2003), COSMOS field at 3 GHz with VLA (Smolčić et al. 2017). In all cases we have scaled the source counts to 1.4 GHz using a spectral index, α ≈ −0.8.

We have found that the normalized differential source counts of THOR and GLOSTAR survey are in good agree-

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The Euclidean-normalized differential source counts of unclassified and unresolved sources detected in THOR and GLOSTAR survey compared with simulated radio sky (left panel) and previously observed source populations (right panel). For details of simulated catalogues and different observed source populations see text.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Smin [mJy]</th>
<th>log₁₀(A)</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>THOR</td>
<td>0.4 (7σ)</td>
<td>−1.38 ± 0.01</td>
<td>1.60 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>−1.71 ± 0.02</td>
<td>1.79 ± 0.04</td>
</tr>
<tr>
<td>FIRST</td>
<td>all</td>
<td>−2.30 ± 0.76</td>
<td>1.82 ± 0.02</td>
</tr>
<tr>
<td>z &gt; 0.5</td>
<td></td>
<td>−1.88 ± 0.46</td>
<td>2.04 ± 0.12</td>
</tr>
</tbody>
</table>

**Table 1.** Best-fit values of amplitude (A) and power-law index (γ) of w(θ) for the unclassified and compact sources in THOR survey and for the all and z > 0.5 samples in the FIRST survey. The best fitted values for various flux density thresholds are also shown.
4 THE ANGULAR TWO-POINT CORRELATION FUNCTION

We have also estimated the ATCF of unclassified and compact sources detected in THOR. We used the LS estimator proposed by Landy & Szalay (1993),

\[ w(\theta) = \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)} \]  

where DD, DR and RR corresponds to pair counts at a separation of angle \( \theta \) for data-data, data-random and random-random catalogue respectively. We have generated a artificial random catalogue containing a large number of randomly distributed sources across the survey area. However, due to non-uniform noise across the survey area all sources with different flux densities cannot be detected across the entire area. In order to incorporate the effect of non-uniform noise in the random catalogue, we have injected 1000 artificial point sources in random positions in each noise map of THOR survey with flux densities drawn randomly from SKADS 1.4 GHz catalogue. Then we have extracted the sources following the same criterion as described in Wang et al. (2018) from this simulated map. The extracted source catalogue gives one realization of an artificial random catalogue where the effect of non-uniform noise is also taken care of. We repeat this process until the artificial random catalogue is 20 times the original data catalogue.

We have used the publicly available code TreeCorr \(^1\) (Jarvis et al. 2004) to estimate \( w(\theta) \). We have binned the sources between 0.1 deg to 50 deg with bin width of 0.1 deg in log scale. We have estimated \( w(\theta) \) of the unclassified and compact sources in THOR survey with flux densities above 0.4 mJy (7\( \sigma \)), 1 mJy and 2 mJy. These flux cuts help us to compare our results with the FIRST survey, which is limited to 1 mJy at 1.4 GHz and also 95% complete at 2 mJy. We expect that beyond 1 mJy flux density threshold, the point source completeness of THOR is more than 99%. The ATCF, \( w(\theta) \), with Poisson error bars is shown in the left panel of Fig. 2. We have also estimated the ‘bootstrap’ errors (Ling, Frenk & Barrow 1986) and found that it is larger than the Poisson errors by a factor of two or three in small scales. Note that Cress et al. (1996) have found a similar trait in error estimates for the FIRST survey.

We have found that for three flux cuts the behavior of \( w(\theta) \) is consistent with each other. There is a decrease in correlation with increasing flux density threshold. In the right panel of Fig. 2, we have compared \( w(\theta) \) with the FIRST survey (Lindsay et al. 2014). They have analyzed the angular clustering of all the FIRST’s sources with flux density above 1 mJy at 1.4 GHz and also studied the clustering of sources with redshifts below and above \( z = 0.5 \). They have found that the high \( z \) sources are strongly clustered and mainly hosted by massive haloes. Siewert et al. (2019) have found a similar features in angular correlation function for LoTSS-DR1 radio sources.

We found that at large scales (\( \theta > 5^\circ \)), \( w(\theta) \) is dominated by systematics and this work is limited up to this scale. The noise properties are an issue even at 7\( \sigma \) threshold and better understanding of noise distribution across the survey is required. Hence, we limit our analysis upto 5\( ^\circ \). We fit the data points in Fig. 2 between 0.1 deg to 5 deg to a power-law of the form:

\[ w(\theta) = A(\theta/\text{deg})^{1-\gamma} \]  

We run Markov Chain Monte Carlo (MCMC) and Metropolis-Hastings algorithm to estimate the parameters by minimizing the \( \chi^2 \) value. The best fitted values of \( A \) and \( \gamma \) for that different flux cuts are mentioned in the Table 3.

\(^1\) https://github.com/rmjarvis/TreeCorr
We also estimate the angular correlation with two different subsets of the whole data set and find that the amplitude of clustering is consistent within the errorbars. We find higher flux cuts exhibit smaller correlation amplitude. Also, the clustering amplitude is higher in comparison with the FIRST survey for all sources. However, the angular correlation for 1 mJy flux threshold is in good statistical agreement with $z > 0.5$ samples of the FIRST survey (Lindsay et al. 2014). This pattern of ATCF suggests that most of these unclassified and compact objects in THOR survey ($\sim 55\%$) may be extragalactic sources at high redshifts.

The excess correlation may be due to the additional correlation present in the artificial random catalogue. This can be the result of unaccounted inhomogeneity of completeness (significant near $5\sigma$ detection threshold) and noise variation across the FoV in generating the random catalogue. However, the artificial catalogue was generated by simulating sources in the noise plane and then extracting those simulated sources. Hence, we do expect that the variation of noise and completeness across the survey area are taken care of during this procedure. Also, the high flux cuts used in this analysis ensures that variation of completeness do not affect the result significantly.

5 CONCLUSION

THOR and GLOSTAR surveys have a large sample of unclassified sources with unknown origin. Here, we study the possibility that they have properties of extragalactic population.

First, we have estimated the differential source counts of unclassified and compact sources in THOR and GLOSTAR survey. There is an excellent agreement of differential source counts with other extragalactic surveys and simulated catalogues. This confirms that these sources are of extragalactic origin.

Furthermore, we studied the ATCF of THOR sources using different flux cuts. We found that the clustering amplitude is higher than the FIRST survey. However, the angular correlation for sources with flux densities above 1 mJy is in agreement with the clustering of high $z$ sources in the FIRST survey. We also found that as we increase the flux density threshold the clustering amplitude decreases. These features suggest that most of these unclassified THOR and GLOSTAR sources could be extragalactic with high redshifts. However, further multi-wavelength (optical, infrared etc) study of these sources are needed to confirm these findings.

This study shows that most of these compact sources detected in different surveys of the Galactic plane are originally of extragalactic origin. So, it is essential to identify or characterize sources detected in these surveys very precisely. There should be one-to-one cross-matching of the sources with other high-frequency catalogues while searching for Galactic compact objects (e.g. compact HI regions, compact components in star forming regions) to avoid possible contamination of extragalactic sources. The ongoing and upcoming surveys with the current or future radio telescopes, like MWA (Tingay et al. 2013), ASKAP (Norris et al. 2011), MeerKAT (Jarvis et al. 2016), SKA (Koopmans et al. 2015) etc, should be cautious about this possible contamination in stuying the Galactic objects.

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REFERENCES


Franzen T. M. O., et al., 2019, PASA, 36, e004


McMullin J. P., Waters B., Schiebel D., Young W., Golap K., 2007, ASPC.,376, 127, ASPC...376
Norris R. P., et al., 2011, PASA, 28, 215
Tingay S. J., et al., 2013, PASA, 30, e007

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