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A C-Band Continuum Map of the Inner Galactic Plane with the Green Bank Telescope

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ABSTRACT

Despite the fact that the Warm Ionized Medium (WIM) is a major component of the Interstellar Medium, our knowledge about it and its relationship with H II regions is very limited. Understanding the WIM better will give us insight into the formation of galaxies and the evolution of high-mass star formation regions. Previous surveys of the WIM and H II regions had low spectral and spatial resolutions or looked at Hα, which suffers from extinction. While single frequency maps can tell us about the presence of ionized gas, radio continuum maps add to our understanding of the extent of this gas far from the sites of high-mass star formation regions. In this paper we provide a first analysis of the C-Band Continuum GBT Diffuse Ionized Gas Survey (GDIGS), which was produced using the Green Bank Telescope. In addition, we assess the quality of such map by comparing it with the C-band map of the Galactic center by Law (2015).

Keywords: WIM, H II Regions, Continuum Map, Galactic Plane, C-Band, GBT.

1. INTRODUCTION

H II Regions and the surrounding Warm Ionized Medium (WIM) can be used to understand high-mass star formation in the Milky Way and other galaxies. Understanding the distribution, state, and relationship of H II regions and the WIM can help us learn more about the evolution of gas in the Interstellar Medium (ISM). They can also be used to compare the Milky Way to other galaxies.

Radio Recombination Lines (RRL) serve as ideal tracers of plasma in the ISM. Previous surveys of the WIM and H II regions observed Hα, which suffers from extinction. Moreover, they had low spectral and spatial resolutions. The GBT Diffuse Ionized Gas Survey (GDIGS) will give us an opportunity to study the WIM and H II regions in much greater detail.

One of the maps that can be produced with this survey is a continuum map. Such a map can give us an overall view on the distribution and relationship of the WIM and H II regions. Using the 64 spectral lines simultaneously recorded by the VEGAS C-band receiver on the GBT, gbtgridder and NOD3 destreaking algorithms we were able to produce the continuum map of the Galactic plane, $32^\circ > \ell > -5^\circ$. We also assess our results by comparing them to a complimentary map of the Galactic center made by Law (2015). One of the goals of this project is to understand if the GDIGS

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data can be used to measure the line to continuum intensity ratio, hence adding scientific value to the existing data set.

2. OBSERVATIONS

The GBT Diffuse Ionized Gas Survey (GDIGS) began in July 2016. In the span of 39 months it observed between $32^\circ > \ell > -5^\circ$ and $b < |1|^\circ$, scanning areas of $1^\circ \times 1^\circ$. The data is collected using an on-the-fly mapping mode and it is Nyquist-sampled. The telescope is moving at the speed of $66''$ per second and the data is collected every 0.3 seconds ($20''$). The telescope scans each point four times, twice in Galactic longitude and twice in Galactic latitude. Every 16 rows (20 minutes) the telescope points 3° above the Galactic plane for calibration. The combination of the C-band receiver and Versatile Green Bank Astronomical Spectrometer (VEGAS) is used to observe 64 spectral lines simultaneously. This includes 22 $\mathrm{H\,n}\,\alpha$, 26 $\mathrm{H\,n}\,\beta$, 8 $\mathrm{H\,n}\,\gamma$, and 8 molecular lines. The beam varies between $2.'93$ and $1.'68$ in the frequency range of 4 to 8 GHz. The resolution of the raw data is 81 pixels per degree.

3. MAPPING ALGORITHMS

For every 1×1 degree map, the raw telescope data was converted into the FITS data format, with 17 cubes across the frequency range using the GBTgridder. We regridded data to be 120 pixels per degree to match earlier maps made for our spectral line data. This process took 3 to 9 hours for each image depending on the file and the machine it was running on.

After removing radio frequency interference (RFI) with a median filter, the continuum maps were produced by taking the median value on the frequency axis of each pixel. This process took an additional 4 to 12 hours for each file.

Then, NOD3 was used in order to get rid of scanning artifacts due to changing weather and RFI. These algorithms utilize basket-weave imaging, crossing points of orthogonally scanned maps to clear the images from artifacts. Then, the data was averaged over two polarizations and all frequencies. Finally, all the files were stitched together using Montage.

Additionally, we attempted to match the background intensities using Montage's correction tool. This work is still ongoing, but judging from trial runs on overlapping and non-overlapping regions it only made the results worse.

4. RESULTS

Current results are located here.[1] A cutout region, similar to Law (2015) map is Figure 2 in the Appendix.

The final map is 4476 by 480 pixels and spans the Galactic plane between $32^\circ > \ell > -5^\circ$. It also extends up to 1.5° from the Galactic plane at the Galactic center and Westerhout 43, which are star formation regions. Some of the regions between $30^\circ > \ell > 19^\circ$ are blank as the data is still being collected and processed.

The lines on edges of $1^\circ \times 1^\circ$ squares are due to unmatched background intensities. Since the observations were conducted across a wide span of time, the varying weather conditions affected the zero value.

[1] https://drive.google.com/file/d/1r5p26cVupYZnpdS1PMeLl6FWj2w4hTLI/view?usp=sharing

The horizontal and vertical bright or dark lines in the data are leftover streaks. Most of them are due to the intensity difference between streaks and the background being too high. This can be fixed by tuning the destreaking algorithms to react better to big jumps in the readings.

A map by Law (2015) was used to check the quality of the results. This map covers several degrees of the Galactic center and was made using data from the GBT in 2003. First, we covered several regions of both maps with masks. Each mask was a circle with the size of the beam. The circles were placed overlapping, at a distance of 1 radius as shown on Figure 1.

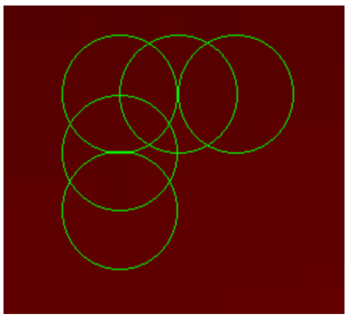

Figure 1. Mask arrangement

To create the set of masks, two programs – `masks_data_GDIGS.py` and `masks_data_jclaw.py` were written. They created a text file for each mask that would cover the given region, recorded maximum and mean flux values from each mask, and recorded the data in a CSV spreadsheet. The masks were placed at a distance from the edges so that the masks would not go outside of the region. Then, the mean and maximum flux values were collected from each of the regions. The next step was to take the ratio of mean values of our data and Law's data at each mask. Since the units of our data are Kelvin and Law's map uses Jy/beam, the expected ratio would be 2.

However, the ratio was not uniform over the maps. The ratio was closer to 2 near the Galactic plane, but the farther away the point was from the Galactic plane, the larger the ratio was. A sample of 200 points is shown in Figure 3.

We looked at whether destreaking algorithms could cause such pattern in the data, but it was not the case. The most likely reason for this is the difference in how the calibration was done in the two projects. In our observations the calibration was done 3° off the Galactic plane. If Law's data had better calibration techniques, it could cause higher signal-to-noise ratio. This would mean that at the bright regions the data in both projects (after unit conversion) would be similar, while the dim regions were different. The values of two maps should be linearly related, $y = mx + b$, where m is the unit conversion factor and b is the offset due to calibration differences. We plotted values of our data from the $1^\circ \times 1^\circ$ files before stitching vs values of Law's data on the area of about 2 square degrees. The linear fit gave us approximately $y = 1.5x + 930$, as shown in Figure 4.

The next step would be to include the whole Law map in the comparison, which will expand the area covered to 5 square degrees. In addition, since some of the scans overlap in the area near the Galactic center, we could use the data from our final map and see if it improves the results by averaging the leftover artifacts. Such comparisons should help us reprocess the GDIGS continuum data to better match the Law (2015) map. In addition, we can assess if other observational protocols might produce better results.

5. CONCLUSION

Even though in the current state the map is far from perfect, in the future it can be used to better understand the Galactic WIM, H II Regions and the link between them. With the final result we will be able to measure the continuum intensity of Galactic H II Regions the WIM. Relying on other data collected through GDIGS, we can also calculate line-to-continuum ratios, which are expected to be around 20 for H II Regions and will help us to differentiate between thermal and synchrotron continuum emission in the Galactic plane.

In order to get the map to the final state we will do the following. First, we would manually go through the raw files and remove the ones that were heavily affected by RFI. Then, we will obtain the conversion rate between our values and the Law (2015) map, which we assume is close to being correct. Finally, we will extrapolate the conversion near the Galactic center to match the background intensities farther away. In addition, we can use CBASS data at 3° off the Galactic plane to improve our calibration. We could also compare different mapping techniques to see if it decreases the amount of artifacts.

Facilities: Green Bank Observatory

Software: GBTIDL, Montage, NOD3

APPENDIX

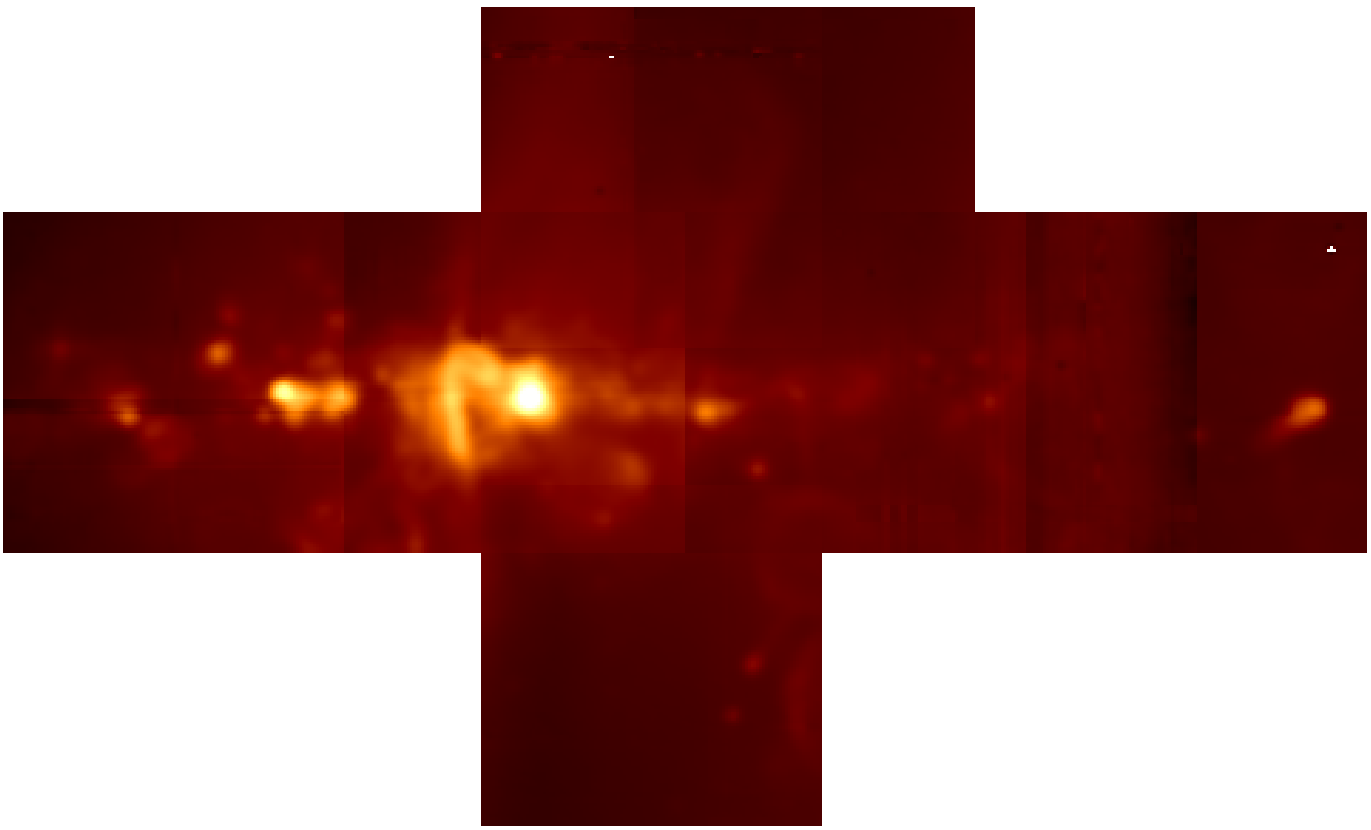

Figure 2. Cutout from the current result. $1.5° > \ell > -2.5$.

REFERENCES

Law, C. 2015, PhD thesis, doi: 10.7910/DVN/28866/MFUSJ8. https://doi.org/10.7910/DVN/28866/MFUSJ8

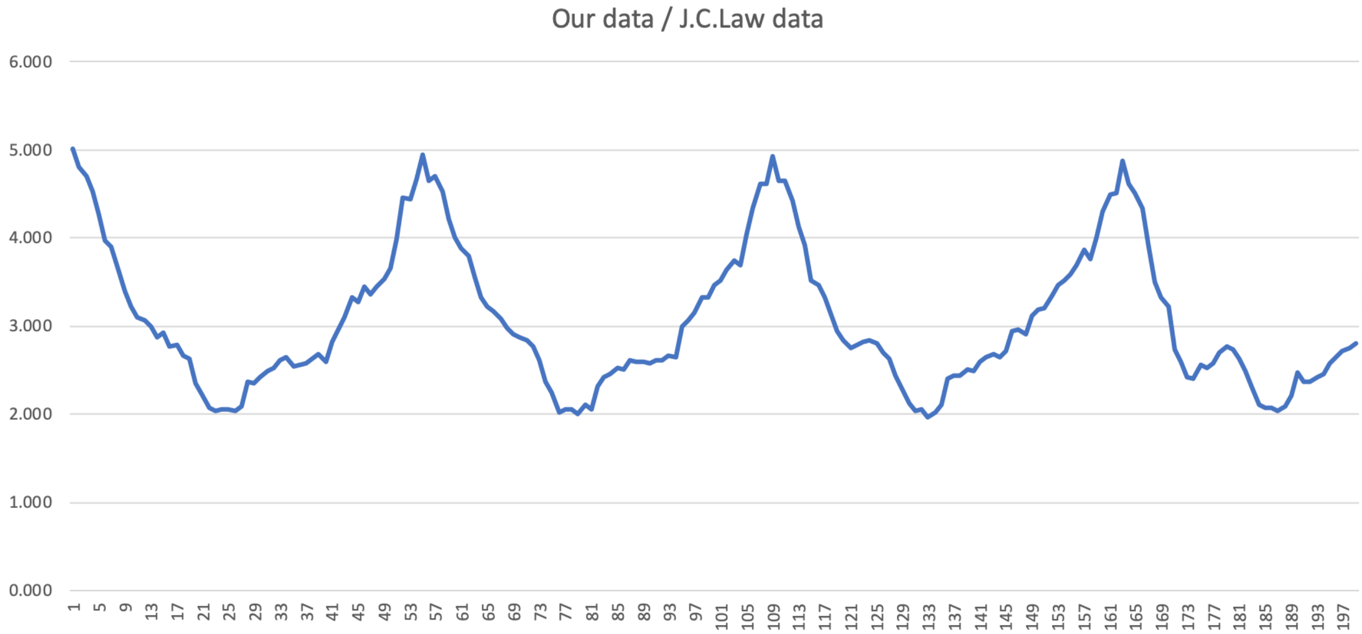

Figure 3. Ratio of our data and J.C.Law's data for 200 points of a square centered at the Galactic center. First point is located at the bottom right corner. Then next point is above the previous until it reaches to the top. After that we start at the bottom again, shifted one to the left. Peaks corresponds to points at the edges; valleys - points closer to the middle.

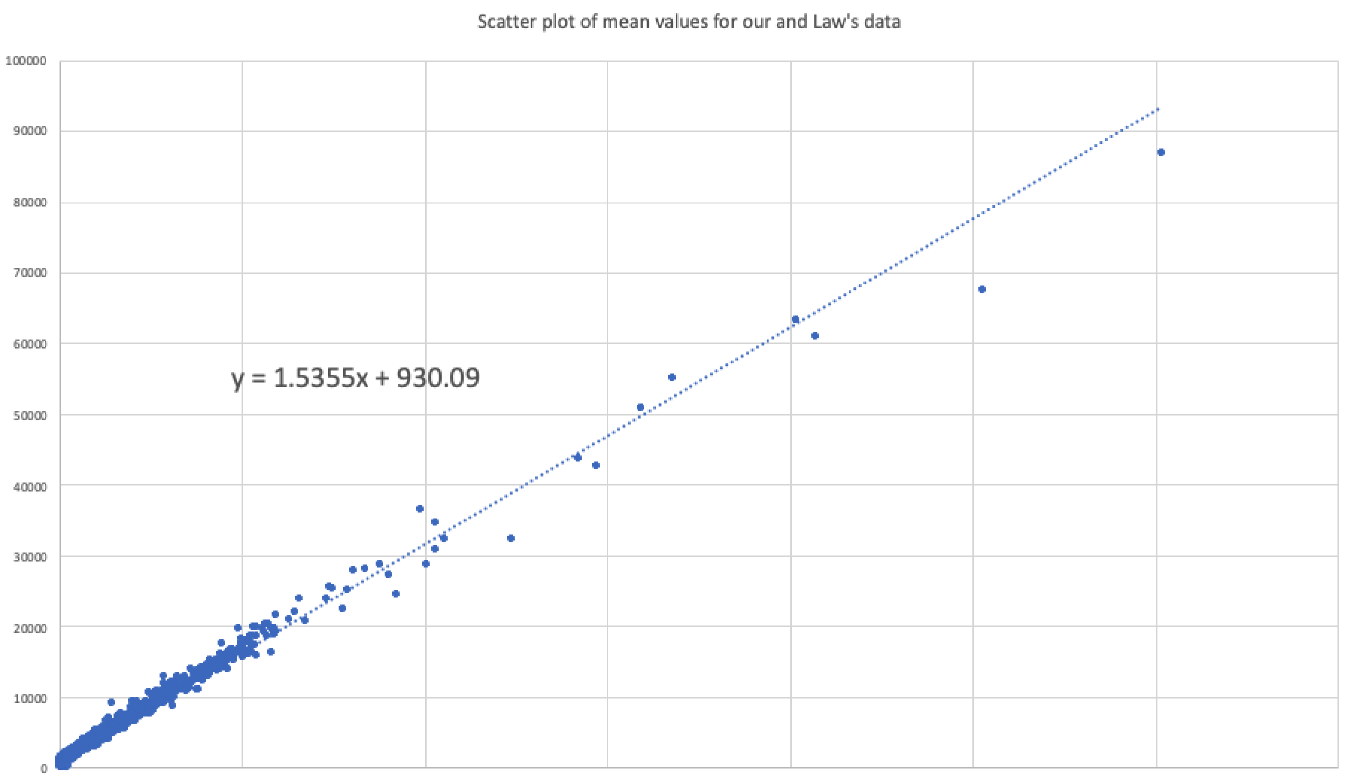

Figure 4. A scatter plot of mean values from each mask for two maps.