VLA P-Band Observation of Teegarden's Star

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ABSTRACT

We investigate Teegarden's Star (also known as GAT 1370, SO J025300.5+165258) for radio emissions caused by magnetic interactions between the star and its planet. This is one of 5 observations to be investigated in a survey that consists of nearby stars that are < 5 pc away. Teegarden's star is a late M dwarf suspected of being a young star with two planets that is thought to have masses of ~1.1 $M_\oplus$ each with orbital periods of 4.91 days and 11.4 days. Being an M dwarf star, it has a strong magnetic field, but the magnetic field of its suspected planet is unknown which is where radio observations come into play. Planetary radio emissions will be evident through excited charged particles in the planet's atmosphere, and/or planetary magnetic field interactions with solar wind. Observational data from the VLA in the P Band (0.23 - 0.47 GHz; 90 cm) and Teegarden's star strong magnetic field allows for reasonable ground-based survey. The Very Large Array (VLA) observed Teegarden's star on August 16, 2016, within the times of 11:31:50 to 12:11:40 (~40 minutes) on the same day. With NRAO's Common Astronomy Software Applications (CASA), we were able to calibrate and image the P Band data - imaging is taken a step further by imaging between the different spectral windows and then by time frames. In our process, we did not find any radio emissions from Teegarden's star but have established an upper limit on P-band radio flux from this system.

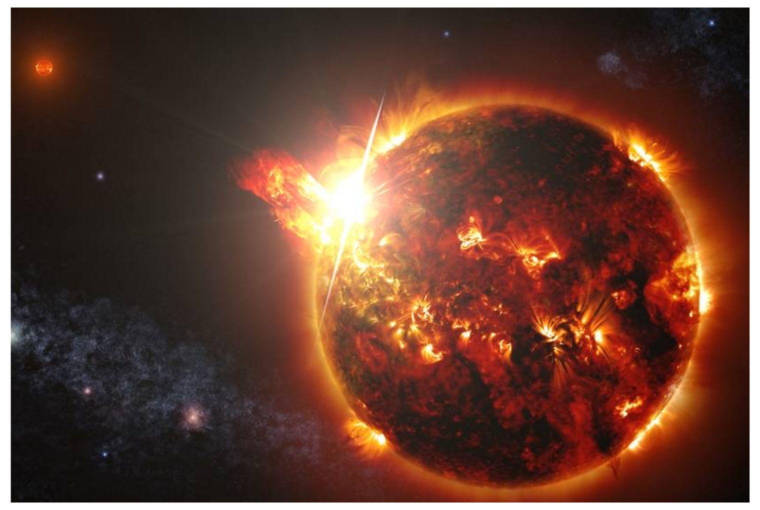


Figure 1: Artist rendering of a M dwarf star from NASA's Goddard Space Flight Center/S. Wiessinger

BACKGROUND

Radio emissions are a form of non-thermal emission that arise from charged particle-magnetic field interactions which can occur from planet-star interaction. Electrons are ejected from the star through solar wind and are attracted and accelerated towards planetary magnetic poles by the power of cyclotron maser instability (CMI) emissions. The impact of the electrons from the solar wind are dependent on the distance of the planet from the star by the Radiometric Bode's Law which states the relationship between solar wind power and planetary radio emission [1]. To the Radiometric Bode's Law, the planet absorbs the power contained in the electrons from the solar wind and a fraction of that power gets converted into radio flux which gives off a radio emission. So, the closer a planet is to the star in the event of solar wind, the solar wind will have a larger power impact which gives off a larger radio flux and radio emission.

To be able to observe these emissions from exoplanets, we would be able to obtain fundamental information of the planet and the strength of the planet's magnetic field [2]. Also, with periodic observations, the rotation periods the planet can be accurately defined.

Teegarden's star was discovered in 2003 and was referred to as a high proper motion star (HPMS) that is main sequence star with the spectral type M6.5V [3]. At that time, Teegarden's star was one of 7 stars with proper motions > 5'' yr^{-1} and ranked third in the list of nearest stellar systems. [4] has detected two planets around Teegarden's star that have a minimum mass of 1.1 $M_\oplus$ with orbital periods of 4.91 days and 11.4 days.

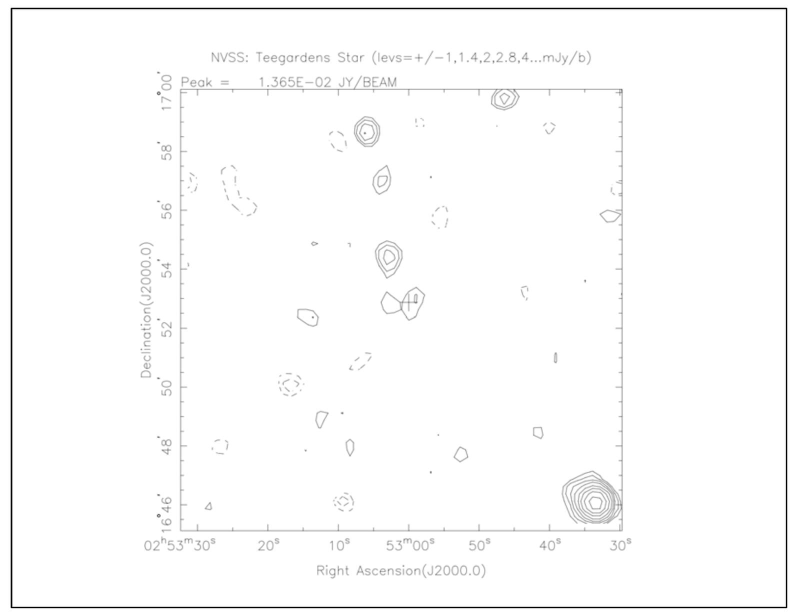


Figure 2: Contour map of Teegarden's star and its surrounding area from NVSS Postage Stamp Server.

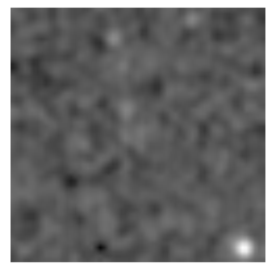


Figure 3: Postage image of Teegarden's star from NVSS Postage Stamp Server.

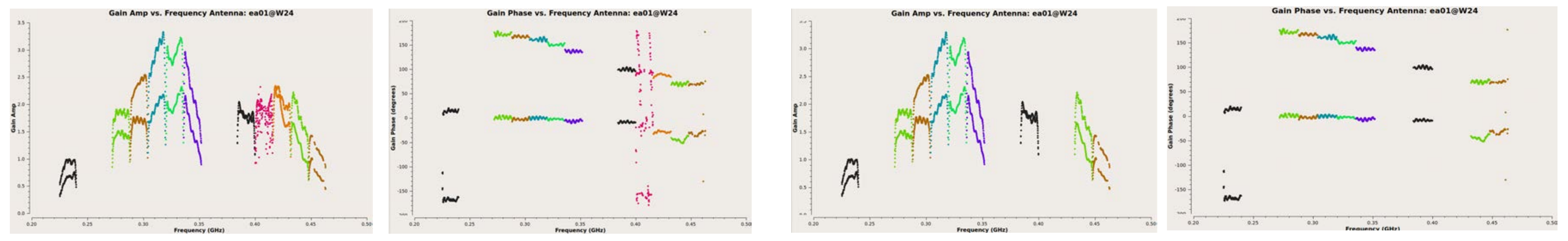
Alias'	GAT 1370, SO J025300.5+165258
RA [deg]	43.26964247679057
Dec [deg]	16.86437381897744
Parallax [mas]	260.9884
Distance [pc]	≈3.8
Spectral Type	M6
T_{eff} [K]	≈ 904
$M_\odot$	≈0.089
Age [Gyr]	≈ >8

Table 1: Information about Teegarden's star from SIMBAD, *Gaia DR3*, and [4]. Teegarden's star's age was calculated in [4].

CALIBRATING & IMAGING

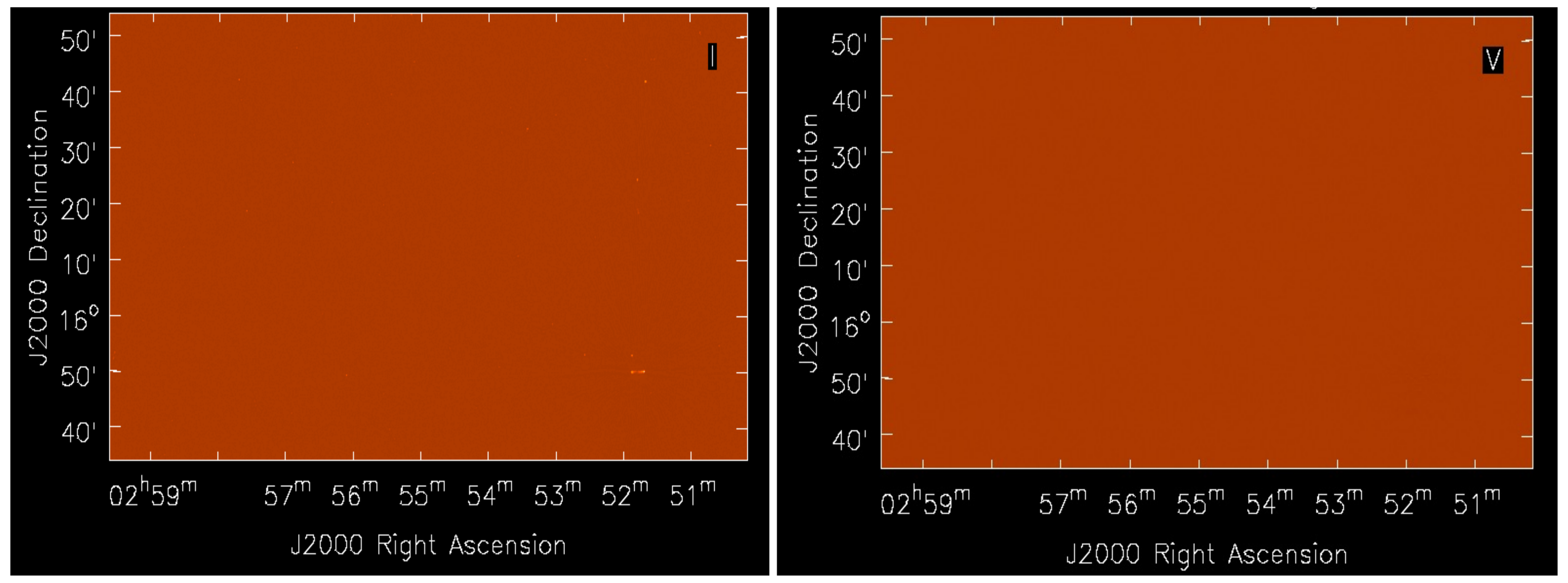
NRAO's Common Astronomy Software Applications (CASA) python program was used to calibrate and image the data obtained from the Very Large Array (VLA).

With the VLA's P Band tutorial to reference, we were able to discard of any data that could not be calibrated such as dead antennas, strong radio frequency interferences (RFIs), and residual outliers. These situations were handled by manual flagging any and all noticeable residual outliers, and CASA's *tfcrop* command - which looks for any outliers missed per scan, per baseline, per spectral window, and per polarization - was used as an automated flagger.



Figures 4 – 7: Before and after manual flagging of gain amp vs frequency and gain phase vs frequency. The pink scatter looked like outliers and did not look like they fit the trend of the surrounding data nor like the data within the VLA's P Band tutorial.

For the imaging, a high number of iterations were used in CLEAN in order to flatten out the prominent beam patterns. Full Stokes bandwidth (IQUV) was used against the full observing time of Teegarden's star in order to spot any radio emission leakage between the Stokes windows. We also wanted Stokes V to check for strongly circularly polarized emission – a characteristic of planetary auroral emission and some types of stellar radio emission. At the end of the imaging, we checked the image statistics for its noise level by looking for the rms value which was rms = 0.3392 mJy/beam.



Figures 8 – 9: Imaging in the whole bandwidth would allow us to check for any leakage - bandwidth I is the only window that has any distinguishable features while V does not show any leakage as Q, U did not as well.
The images have been zoomed in on the general area around Teegarden's star.

CATALOGUE CROSS MATCHING

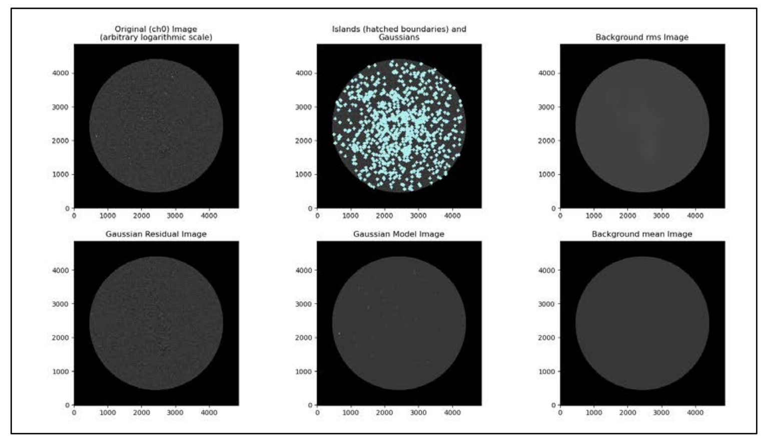


Figure 10: PyBDSF image results from cleaned image.

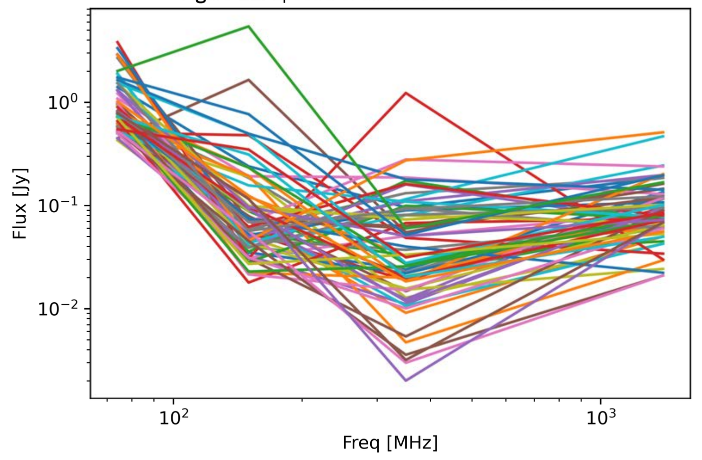
Now that we have our cleaned image, we can extract sources from our image by putting it through the Python Blob Detector and Source Finder (PyBDSF) to find out what those extracted sources are. Then, we can cross match the extracted sources with all sky surveys, gather the common sources and their fluxes, and plot them against each other to obtain a spectra (Figure 14) – since there is a characteristic spectral shape for extragalactic sources, we can assume the spectral shape of the common sources' fluxes.

PyBDSF extracted ~900 sources from the cleaned image.

With a search radius of 6º (primary beam size) and a max distance of 26.4'' (synthesized beam size) out from Teegarden's star, we were able perform cross matches with the following all sky surveys using ViZier's XMatch:

- VLA Low Frequency Sky Survey (VLSS) at 74 MHz
- NRAO VLA Sky Survey (NVSS) at 1.4 GHz
- The GMRT All-Sky Radio Survey (TGSS) at 150 MHz

Figure 11: Spectra of all cross matched data.



Tables Crossed	Sources Matched
NVSS × VLSS	≈300
Extracted × (NVSS × VLSS)	≈60
Extracted × TGSS	≈600

Table 2: NVSS and VLSS were cross matched with each other to get initial matches with them being the biggest catalogues of the list.

SPECTRUMS & LIGHTCURVES

CLEAN was used to image the data along each spectral window (0~15) individually with the full observing time in order to get spectrum at each spectral window. Then, we divided the observing time of Teegarden's star into ten ~4-minute time intervals and kept all spectral windows to obtain a spectrum at each time window.

To get an accurate read on Teegarden's star, sub-images from each of the spectral window and time window images were made then we took the rms value of each image to create upper limit plots.

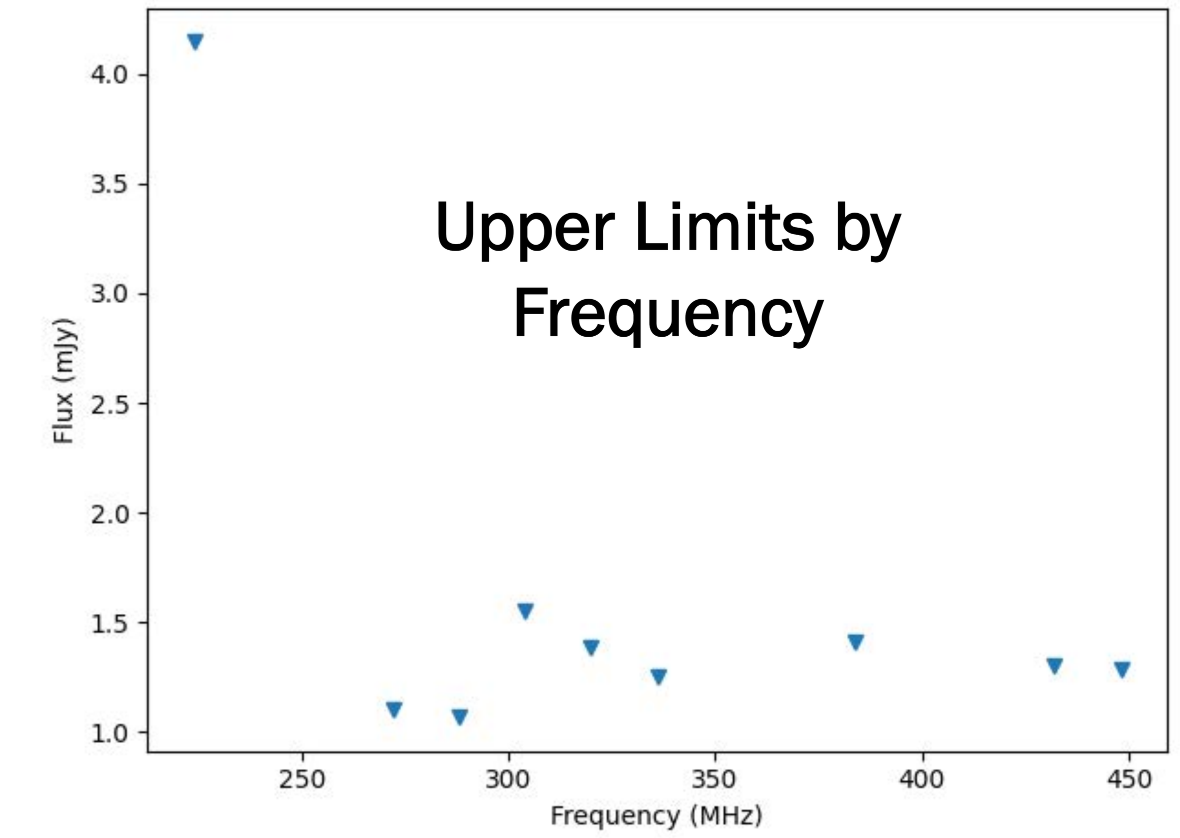


Figure 12: Upper limit plot of frequency vs flux. Only 9 frequency points out of 16 are plotted because there were only 9 spectral windows that produced images within the full time range – it is suspected that the data within the spectral windows that did not produce images were too heavily flagged, so it did not have usable data to clean any further. The high point in the first spectral window is also suspected of being heavily flagged thus giving a high flux output.

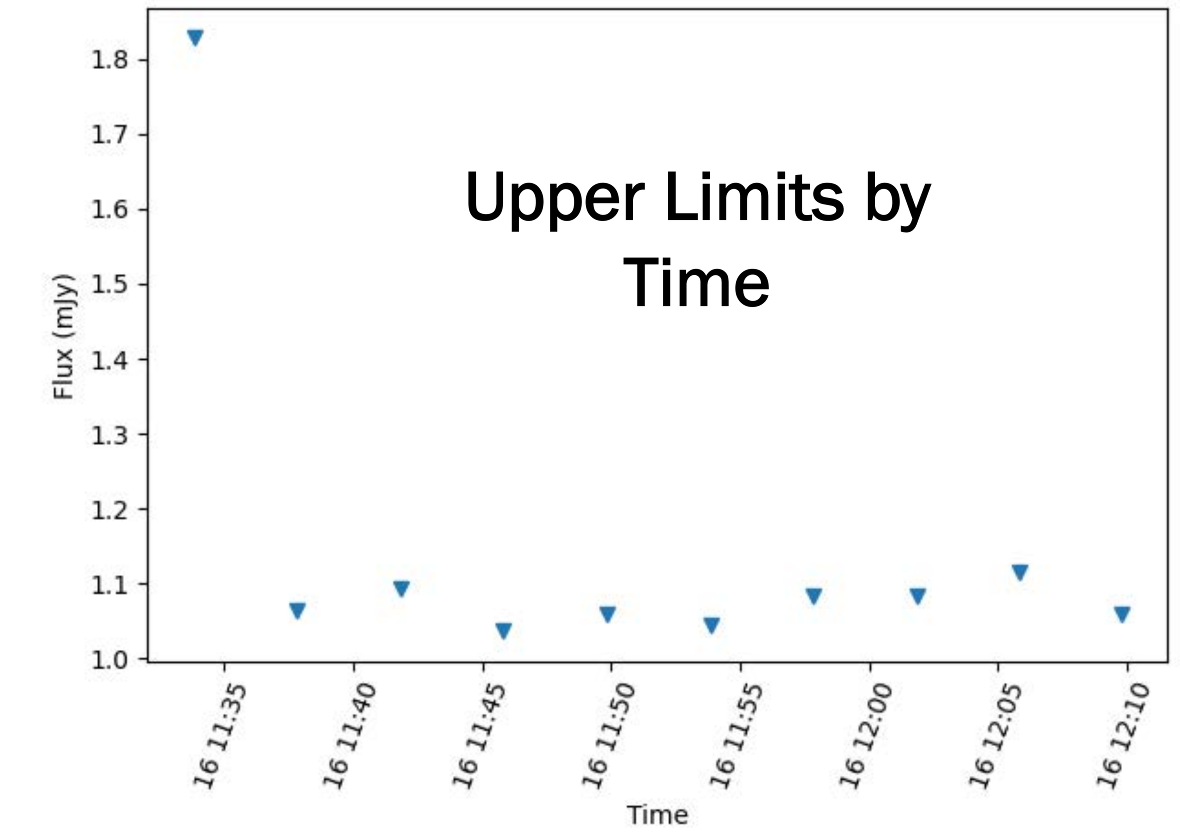


Figure 13: Upper limit of time vs flux. There were a total of 10 time interval, each having 4 minutes in each interval and each frame was able to produce an image. The high point in the first interval is suspected of being heavily flagged thus giving a high flux output.

RESULTS & DISCUSSION

In this observation, we did not find any radio emissions from Teegarden's star.

Though, there are 4 more observations of Teegarden's star in the P Band to be calibrated and imaged. The work done in this observation will serve as a framework with reusable script for doing the same analysis on the other observations.

References: [1] Desch, M. D., & Kaiser, M. L. 1984, Nature, 310, 755; [2] Farrell, W. M., Desch, M. D., & Zarka, P. 1999, Journal of Geophysical Research, 104, 14205; [3] Teegarden, B. J., Pravdo, S. H., Hicks, M., et al. 2003, The Astrophysical Journal, 589, L51; [4] Zechmeister, M., Dreizler, S., Ribas, I., Reiners, A., & et. al. 2019, Astronomy Astrophysics, A49, 1