Pulse Profiles and Polarization of the Terzan 5 Cluster Pulsars

Ashley R. Martsen, Scott M. Ransom
This work was done with the NRAO as part of an REU funded by the NSF
(Dated: August 31, 2021)

Terzan 5 is a globular cluster in our galaxy that is home to 39 millisecond pulsars. The Terzan 5 pulsars are faint, and in general the polarization data has too low signal-to-noise ratios to be able to be analyzed. We combined over eleven years worth of archival GBT data to create high signal-to-noise profiles for the majority of the pulsars in the Terzan 5 cluster. Due to an instrumental issue, some of the polarization information was contaminated and was excluded from the polarization profiles. We also created higher signal-to-noise Total Intensity pulse profiles using all the data including the contaminated data, as the total intensity data was uncontaminated by the instrumental issues. We created both high signal-to-noise polarization and total intensity profiles for 35 pulsars in the Terzan 5 cluster in two different frequency ranges. These high signal-to-noise profiles will be the basis for new pulse profile templates for improved timing of the pulsars.

Introduction

Pulsars are a type of stellar remnant that are created when a large star runs out of fuel to burn. The result of the lack of fuel to continue fusion is the star undergoing a supernova explosion. If the remnant left over from the supernova is not massive enough to turn into a black hole, it will become a neutron star[1]. If said neutron star is rotating and magnetised enough it will emit electromagnetic radiation from the magnetic poles. If the axis of rotation is misaligned with the axis of magnetization, we can observe the beam of light as a pulsation, which we refer to as Pulsars[2]. These pulsars are rapidly spinning, with periods between 23 seconds and 1.4 milliseconds depending on the pulsar[3].

Globular clusters are known to be very good environments for the formation of millisecond pulsars. This is because of the high density of stars there are many binary systems. These means that if one of the stars in a binary systems goes supernova, there will be a system with a neutron star and a main sequence star[45]. For these systems where the distance between the two objects is small, when the main sequence star fills its Roche Lobe, the neutron star can accrete matter from its companion. These systems allow the neutron star to gain angular momentum and decrease the spin period toward the millisecond range[6].

The Terzan 5 globular cluster is a cluster in the Milky Way galaxy. Specifically Terzan 5 is located toward the galactic center at 17h 48m 05s, -24° 46′ 48”[1] and is 5.9 kpc away from Earth[7]. This is relatively far away for observations of pulsars, which means that our detections are often very faint. Terzan 5 contains 39 pulsars that we know of, all of which are millisecond pulsars[8].

The emission we detect from pulsars also tends to be highly polarized[1]. This polarization can be in the form of linear polarization or circular polarization. Linear polarization is when the oscillating electric fields are all or mostly aligned, unlike in unpolarized light when the oscillating fields are evenly distributed among all possible angles[9]. The other form of polarization is circular polarization in which the wave angle observed rotates at a constant rate. The great distance to the Terzan 5 cluster makes their detection and polarization information very faint which is why summing the data can be very informative. An example of the difference that combining the data can make is included in Figure 1

The way polarization data is reported is by using what is known as the Stokes Parameters[10]. The four Stokes Parameters are I, Q, U, V. I is the total intensity, both polarized and non-polarized emission. Q and U are two orthogonal components used to calculate the linear polarization, L. Specifically the equation for L is as follows.

$$L = \sqrt{Q^2 + U^2} \tag{1}$$

While L contains valuable information about the linear polarization, it does not include any information about the angle that the linear polarization is coming at, compared to an arbitrary 0 angle. The angle is known as position angle, PA, and the way the PA changes throughout the pulse phase can inform our understanding of the emission mechanism. The equation for PA is given as the following.

$$\Phi = \arctan Q/U \tag{2}$$

The last Stokes parameter is V, which is the circular polarization. V is able to be both positive and negative, whereas L is restricted to being positive due to its calculation. The positivity or negativity of V is defined by the polarization either being right-hand circular or left-hand circular; and which is defined to be positive is left to what convention is being used. Both conventions are popular to use.

Polarzation information can inform our understanding of many things. The linear polarization from pulsars can be used to measure the Rotation Measure (RM) between us and the source. The RM is the measurement of the strength of the Faraday Rotation that the interstellar medium is causing on the emission[11].

[1] The coordinates are taken from Simbad

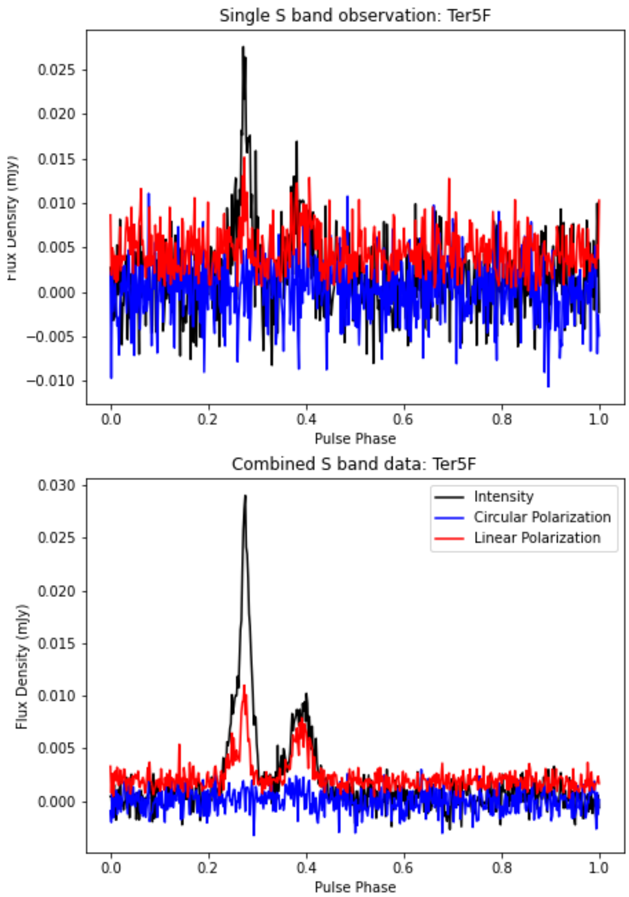

FIG. 1: Example of the difference between a single observation and the combined observations for Terzan 5 F. The horizontal axes is the pulse phase, and the vertical axes are the Intensities. The black lines are the total Intensities, the red lines are Linear Polarization. The blue line is the Circular polarization. As can be seen, the combining of the data brings out a lot of information from the noise, including polarization data.

Faraday Rotation is when the magnetic fields of the galactic ionized medium cause a rotation of the polarized light. Understanding the RM can help inform our understanding of the galactic magnetic fields and aid in mapping them. Due to the fact that Terzan 5 is a globular cluster, the angular separation between each pulsar is very small which would allow for small scale mapping of the galactic magnetic fields[12]. This is typically very hard to accomplish as it would require being able to distinguish the RM differences on a small separation scale. This means that strong signal-to-noise for polarization data for the Terzan 5 pulsars would be useful for this as well as understanding more about the pulsars themselves.

Methods

The data used were all archival Green Bank Telescope observations taken over many years. Two different frequencies were observed; the L band centered at 1500 MHz, and the S band centered at 2000 MHz. Both frequency ranges had bandwidths of 800 MHz. The observations were taken over eleven years in one of these two frequencies. Due to the long time frame of observations, two different back-end machines were used; GUPPI[13] and VEGAS[14]. The GUPPI machine was used for all observations from 2010 until late 2019 when the observations using the VEGAS back-end began.

For S band observations, there were 30 observations with the GUPPI machine and 9 observations with the VEGAS back-end. However due to a malfunction with the GUPPI machine in 2014, much of the later GUPPI polarization data was corrupted. For the polarization data, only 9 of the 30 GUPPI observations were usable. For the L band data, there were 28 GUPPI observations of which 20 had non-corrupt polarization data, and 3 VEGAS observations.

The methods for the S band and the L band were the same. First each observation was calibrated and had RFI removed using PSRCHIVE[15] functions. Once the data has been calibrated and cleaned, each observation data cube was averaged over the time axis also known as t-scrunched. This was done using PSRCHIVE's pam -T function. T-scrunching folds the data from the pulse period, so that average pulse from the observation is found. This left the data with axes of frequency, pulse phase, and intensity. Once all the observations for a given band were cleaned and t-scrunched, all the same back-end data was combined. This is to say, for a single observation band, GUPPI data was combined with GUPPI data and VEGAS data was combined with VEGAS data. The combining process was done using the PSRCHIVE function psradd along with the -P option to align the data by where the peak in the pulse phase is. See Figure 2.

This process results in two combined observations for each band: the GUPPI data and the VEGAS data. There were slight differences in how the GUPPI machine and VEGAS machine records the data: specifically the polarization data are all sign flipped between the back ends due to differing conventions used, which can be seen in Figure 3. Another difference is the center frequencies are misaligned by a single bin. To combine the GUPPI and VEGAS data, the data was averaged over the frequency or f-scrunched to void the issue with the center frequencies. Similar to t-scrunching, this was done with PSRCHIVE's pam function. This resulted in only pulse profiles with polarization data.

Lastly the sign for the polarization data were flipped in python, and the GUPPI and VEGAS data combined to give accurate and high signal-to-noise profiles for each pulsar in the given band.

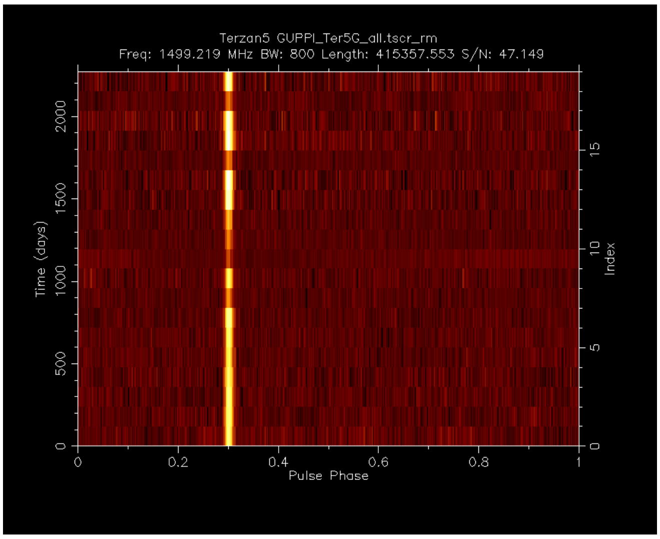

FIG. 2: Example of the alignment of each observation for Terzan 5 G using the GUPPI back-end in the L band frequency range. The horizontal axis is the pulse phase, and the vertical axis is observations. Each horizontal line is an observation that was time scrunched. Each observation was frequency scrunched to show this image. As can be seen in the image, all the observations are aligned so that the pulse peak is at the same position in the pulse phase. This means when the pulses are averaged together correctly.

Results

The results for this project are the highest signal-to-noise profiles for the Terzan 5 pulsars. For each pulsar there are four pulse profiles made. The profiles are either in S band or L band, and either contain polarization data, or solely intensity data with an even higher signal-to-noise level.

Of the 39 pulsars in Terzan 5, the results include all but four. The four excluded pulsars are given in the following, with a short explanation of why there were excluded. Ter5A was excluded due to it's highly extreme binary orbit and eclipsing nature, aligning the observations was proven to be difficult. An example of this misalignment is shown in Figure 4. Ter5P and Ter5ad were excluded due to their extreme binary orbit and the difficulty in observing them due to faintness and long-duration eclipses. Ter5al was excluded on account of how faint it is and the limited observations, along with the fact that Ter5al does not yet have a timing solution so aligning the pulses would be very difficult.

The final profiles created from this work are shown in Appendix A. The specific lengths of observing time that went into each profile collection is different. For the polarization profiles, in the S band there is about 3.0 days worth of observations and in the L band 5.7 days. The Total Intensity profiles contain in the S band, 5.2 days worth of observations. The L band has 6.6 days for Total Intensity. These values are for the ideal case assuming that the specific pulsar was detectable in all the observations used.

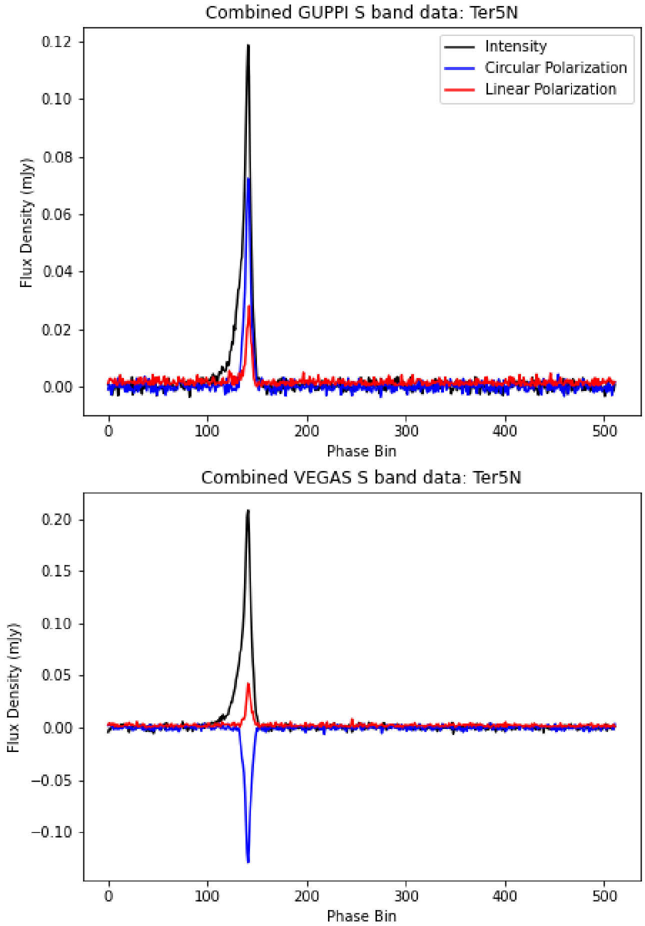

FIG. 3: Example of the different conventions used between the GUPPI and VEGAS back-end. Both images are of Terzan 5 N in the S band, combining all the observations for each back end. As can be seen, the GUPPI data has a strong positive circular polarization while the VEGAS has strong negative circular polarization. This difference is not inherent to the pulse, and is instead a feature of how the GUPPI and VEGAS machines use different conventions for polarization. Mainly that one assigns a positive value to right handed polarization while the other assigns a negative value. Due to the way linear polarization is calculated, the sign difference is not apparent between the GUPPI and VEGAS data.

Conclusion and Future Work

In conclusion, this project has created higher signal-to-noise Intensity profiles than we previously had for each pulsar. This will be useful in more accurately timing the pulses due to the more precise peak in the pulse shape. This project has also created higher signal-to-noise polarization data, which can be used to calculate more precise RM values for each pulsar. Calculating **precise** RM val-

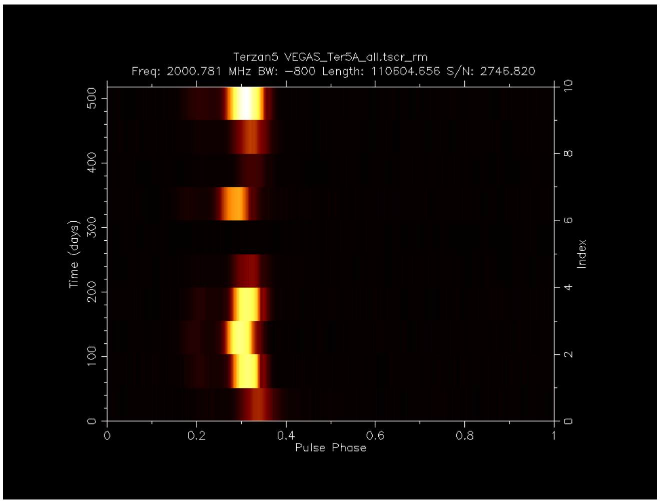

FIG. 4: Example of the misalignment of each observation for Terzan 5 A using the VEGAS backend in the S band frequency range. The horizontal axis is the pulse phase, and the vertical axis is observations. Each horizontal line is an observation that was time scrunched. Each observation was frequency scrunched to show this image. As can be seen in this image compared to Figure 2 the bright pulses are not in a straight line across observations and if added together would add out of phase.

ues for each pulsar is the next **step** that this project would take. Having the RM values for each pulsar will allow for more precise timing solutions to be created for each pulsar as well as more detailed mapping of the galactic magnetic fields in the direction of Terzan 5. These are out of the scope of this project, but are important to the greater astronomy community.

Other future steps for this specific project would be to continue to observe these pulsars and gather more data. These data could than be added to get even better signal-to-noise, especially for the faint pulsars that still have relatively poor signal to noise values. This specific step is will likely be left for another student as the time to gather enough observations to warrant continuing with this project would take many years. Since the observations of Terzan 5 used were archival and more observations will continue to be taken, it is possible to revisit this project in a number of years to further update the profiles with little extra work needed to be done.

Acknowledgments

I would like to thank Dr. Scott Ransom for his guidance and help this summer, as well as his research group for any and all aid they have provided me. Dr. Jim Braatz, Dr. Will Armentrout, Dr. Anna Kapinska, and all the people involved with the GBO/NRAO REU that allowed me to have this opportunity. Lastly I would like to acknowledge the NSF for their funding for my REU.

[1] J. J. Condon and S. M. Ransom, *Essential Radio Astronomy* (Princeton University Press, 2016), ISBN 978-0-691-13779-7.
[2] A. Philippov, A. Timokhin, and A. Spitkovsky, Physical review letters **124**, 245101 (2020).
[3] B. Bhattacharyya and J. Roy, *Radio millisecond pulsars* (2021), 2104.02294.
[4] S. M. Ransom, C. Bassa, Z. Wang, A. Cumming, and V. M. Kaspi, AIP Conference Proceedings (2008), ISSN 0094-243X.
[5] A. Ridolfi, T. Gautam, P. C. C. Freire, S. M. Ransom, S. J. Buchner, A. Possenti, V. Venkatraman Krishnan, M. Bailes, M. Kramer, B. W. Stappers, et al., **504**, 1407 (2021), 2103.04800.
[6] R. H. H. Huang, A. K. H. Kong, J. Takata, C. Y. Hui, L. C. C. Lin, and K. S. Cheng, The Astrophysical Journal **760**, 92 (2012), ISSN 1538-4357.
[7] S. Bogdanov, A. Bahramian, C. O. Heinke, P. C. C. Freire, J. W. T. Hessels, S. M. Ransom, and I. H. Stairs, Astrophys. J. **912**, 124 (2021), 2012.12944.
[8] Z. Pan, X.-Y. Ma, L. Qian, L. Wang, Z. Yan, J.-T. Luo, S. M. Ransom, D. R. Lorimer, and P. Jiang, Research in Astronomy and Astrophysics **21**, 143 (2021), 2103.14927.
[9] S. Huard, *Polarization of Light* (1997).
[10] D. R. Lorimer and M. Kramer, *Handbook of Pulsar Astronomy*, vol. 4 (2004).
[11] H. M. Wahl, M. McLaughlin, P. A. Gentile, M. L. Jones, R. Spiewak, Z. Arzoumanian, K. Crowter, P. Demorest, M. E. DeCesar, T. Dolch, et al., *The nanograv 12.5-year data set: Polarimetry, rotation measures, and galactic magnetic field strengths from nanograv observations with the green bank telescope* (2021), 2104.05723.
[12] C. Sobey, S. Johnston, S. Dai, M. Kerr, R. N. Manchester, L. S. Oswald, A. Parthasarathy, R. M. Shannon, and P. Weltevrede, **504**, 228 (2021), 2103.13838.
[13] R. DuPlain, S. Ransom, P. Demorest, P. Brandt, J. Ford, and A. L. Shelton, in *Advanced Software and Control for Astronomy II*, edited by A. Bridger and N. M. Radziwill (2008), vol. 7019 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 70191D.
[14] R. M. Prestage, M. Bloss, J. Brandt, H. Chen, R. Creager, P. Demorest, J. Ford, G. Jones, A. Kepley, A. Kobelski, et al., in *2015 URSI-USNC Radio Science Meeting* (2015), p. 4.

[15] W. van Straten, P. Demorest, and S. Oslowski, Astronomical Research and Technology **9**, 237 (2012), 1205.6276.

Appendix A: Profiles

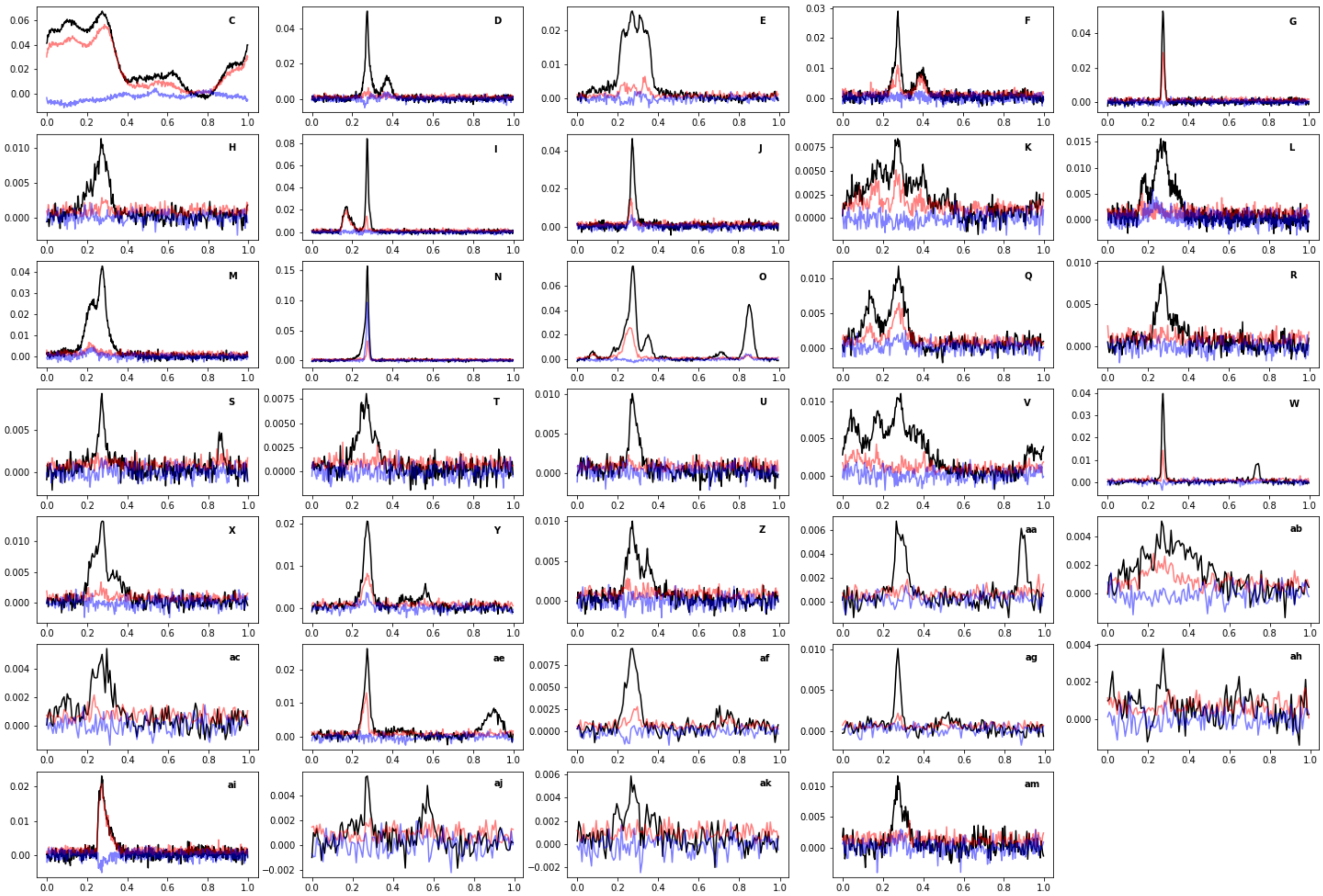

FIG. 5: S band Polarization Table. 256,697 seconds worth of observations combined.

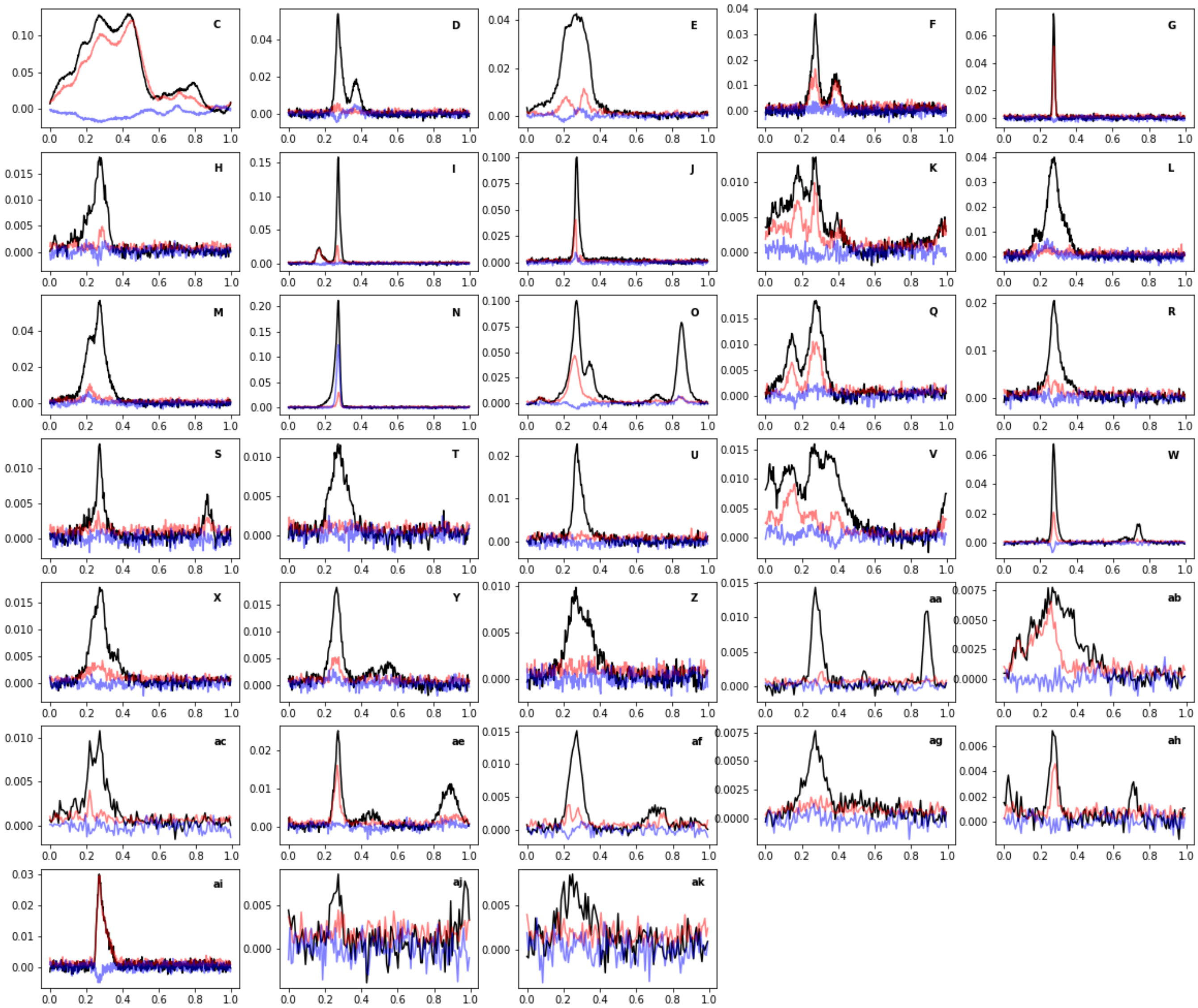

FIG. 6: L band Polarization Table. 494,567 seconds worth of observations combined.

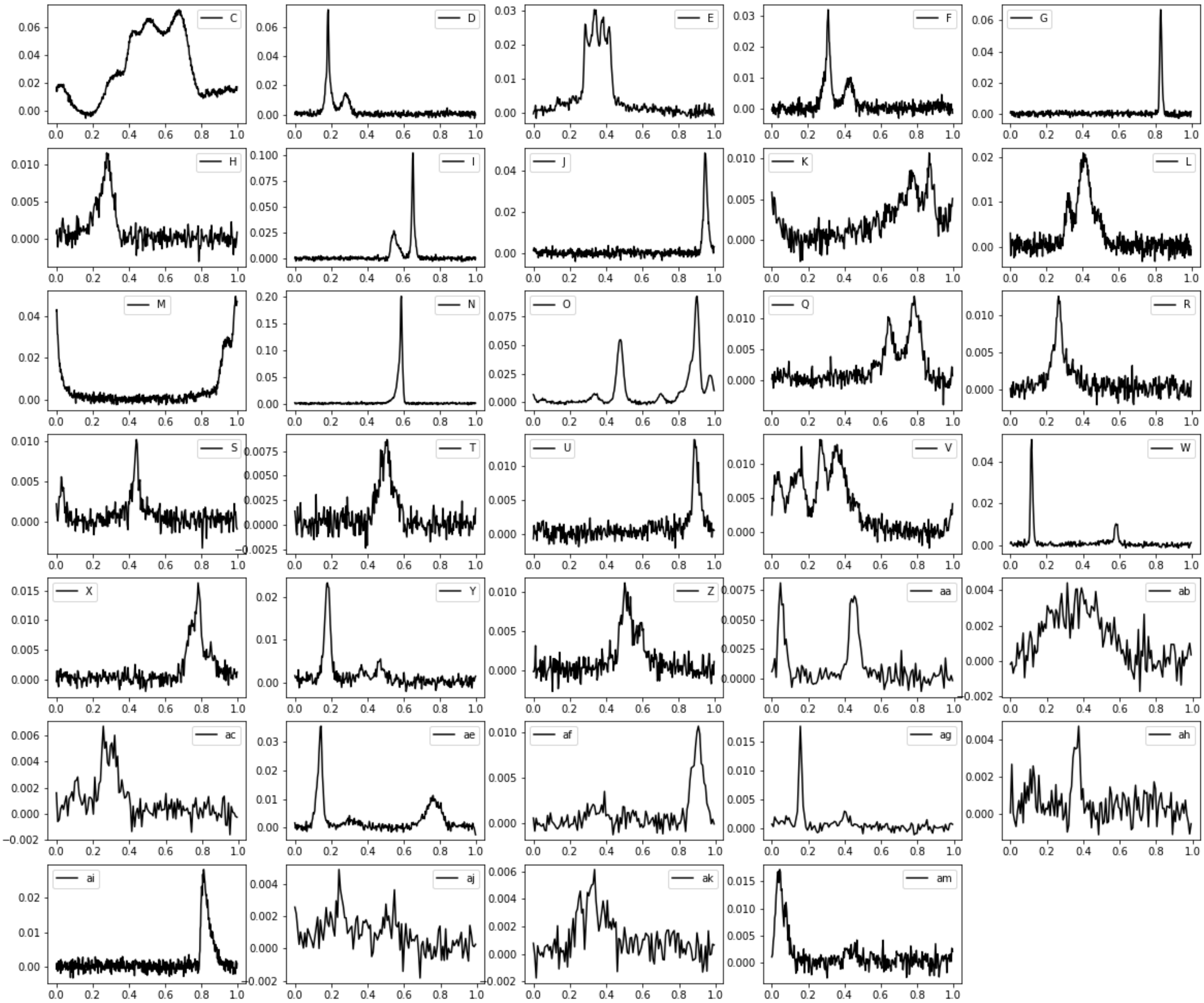

FIG. 7: S band Intensity Table. 449,652 seconds worth of observations combined.

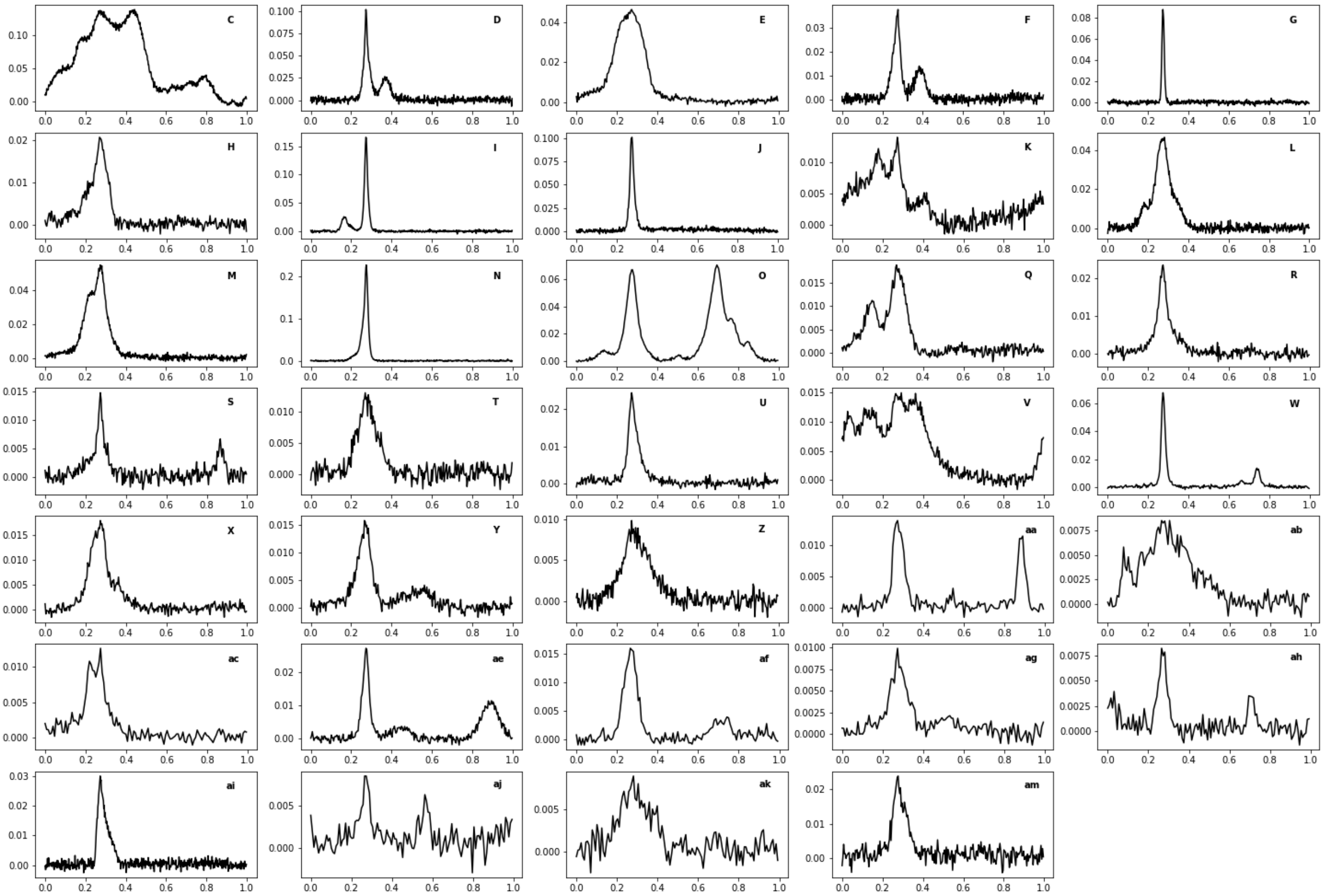

FIG. 8: L band Intensity Table. 567,976 seconds worth of observations combined.