Analyzing Nulling Pulsars Using Gaussian Mixture Models

T. Fichtenbauer, J. K. Swiggum, D. L. Kaplan, and the GBNCC Collaboration
University of Wisconsin-Milwaukee

Nulling Pulsars

- Pulsars are massive, rapidly rotating, compact objects that emit electromagnetic radiation from highly magnetized poles
- Roughly 10% of the pulsar population occasionally ceases radio emission for many pulse periods; these are called **nulling** pulsars (Backer 1970)
- Intrinsic mechanism for nulling not understood (Gajjar et al. 2012)
- Attempts to correlate **nulling fraction** (NF) with various measurable/derived parameters disagree:
  - Ritchings (1976) and Wang et al. (2007) claim correlation between nulling fraction and pulsar's age
  - Biggs (1992) claim stronger correlation between NF and spin period
- Previous measurements of NF were biased, not robust
- More precise & robust measurement of the NF → more meaningful correlations
- Goal: tie correlations to understanding of pulsar emission& evolution

Source Selection and Data Reduction

- Focused on 15 pulsars discovered in the Green Bank North Celestial Cap (GBNCC; Stovall et al. 2014) survey that exhibited nulling
- Each pulsar was observed for ~2 hr using the 100-m Robert C. Byrd Green Bank Telescope (GBT)
- Raw data processed by folding the data such that each sub-integration was exactly one pulse, manually removing radio frequency interference
- Produced integrated pulse profiles, manually defined ON/OFF-pulse windows
- Used Kaplan et al. (2018) to create ON/OFF histograms, calculate both a Ritchings (old) and Gaussian Mixture Model (new) NF

Old Method of Analysis

- **Ritchings (1976)** method defines two regions of the integrated pulse profile: the OFF-pulse window (noise) and the ON-pulse window (signal): see Figure 1a
- ON/OFF intensities are calculated by summing over each pulse and binned into histograms ON_n and OFF_n: see Figure 1c
- Trial NFs are then chosen until the difference between the ON histogram and the product of the nulling fraction and the OFF histogram equals 0 (Figure 1c)

$$\left| \sum_{I_n<0} \mathrm{ON}_n(I^{\mathrm{ON}}) - \mathrm{NF} \times \mathrm{OFF}_n(I^{\mathrm{OFF}}) \right|$$

- Drawbacks: imposes arbitrary histogram binning; assumes negative intensity values from the ON-window are entirely due to nulling
- To limit bias and inaccuracy in the analysis of nulling pulsars, we introduce a new method of analysis—**Gaussian Mixture Model** (Kaplan et al. 2018)

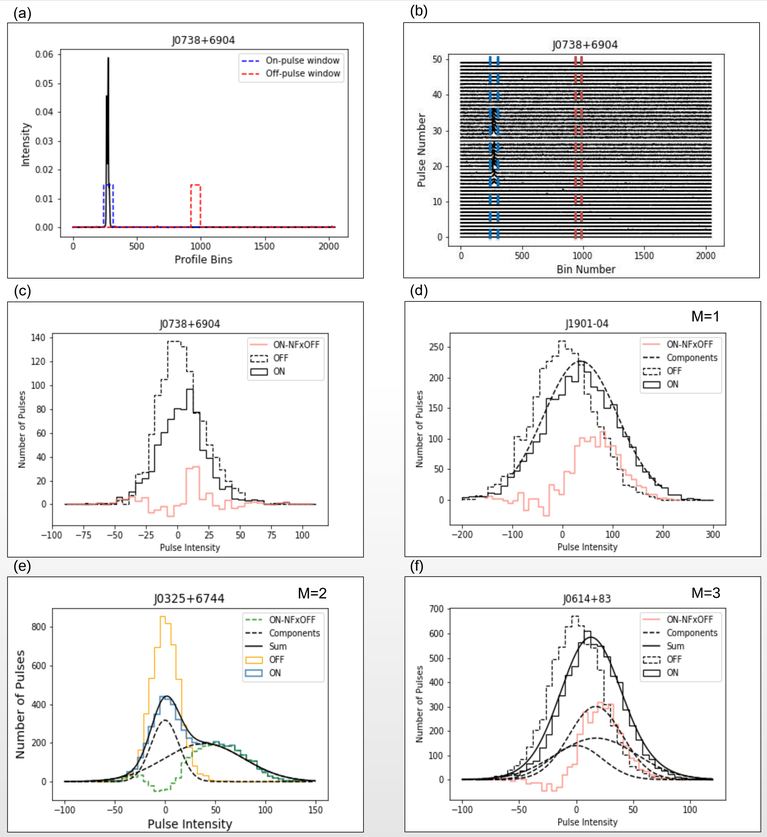

Figure 1. (a) Integrated pulse profile for J0738+6904 with defined ON/OFF windows; (b) single pulse plot for J0738+6904 with defined ON/OFF windows; (c) histograms for ON/OFF intensities, as well as adjusted nulling fraction histogram for J0738+6904 (this pulsar has a high S/N ratio, making it ideal for GMM analysis, but due to the large separation between the emitting and nulling intensities, the components could not be plotted); (d-f) ON/OFF intensities and adjusted nulling fraction histograms, with components (M) ranging from 1-3 that make up the ON pulse histogram

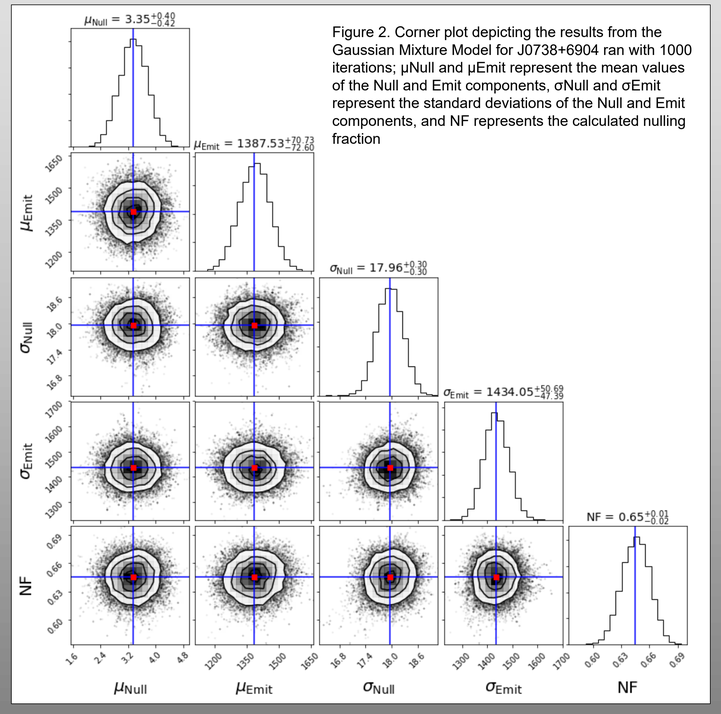

Figure 2. Corner plot depicting the results from the Gaussian Mixture Model for J0738+6904 ran with 1000 iterations; μNull and μEmit represent the mean values of the Null and Emit components, σNull and σEmit represent the standard deviations of the Null and Emit components, and NF represents the calculated nulling fraction

Gaussian Mixture Model (GMM)

- Uses same ON and OFF pulse windows defined by the Ritchings' method (Figure 1a)
- Applies Gaussian Mixture Model w/ Markov Chain Monte Carlo (MCMC) to determine more accurate and less biased NF (Figure 1d)
- Allows for negative pulse amplitudes just from noise, even when ON (just low S/N)
- Allows for multiple components: 1 (no nulling), 2 (nulling), 3 (more complex behavior), …; evaluated using Bayesian Information Criteria
- These ON/OFF intensity distributions were then fed into the GMM to determine best-fit parameters with uncertainties (Figure 2)
- Number of components also varied

Results and Conclusions

- Looked at 15 pulsars
- Ritchings method systematically over-estimates the NF, except for J0738+6904 (supported by simulations in Kaplan et al.; see Figure 3)
- 6/15 pulsars analyzed with GMM do not exhibit nulling behavior: best-fit number of components is 1
- In the future will apply broadly to get un-biased view

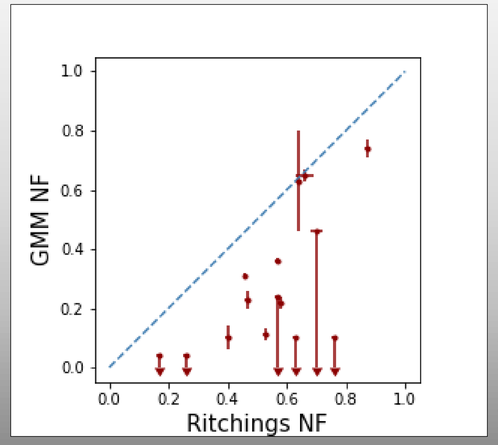

Figure 3. Calculated GMM NFs vs. calculated Ritchings NFs. Upper limits are for sources with no apparent nulling. The tendency of the Richtings method to over-estimate NF is clear.

References

Backer, D.C. 1970, Nature, 228, 42
Biggs, J.D. 1992, ApJ, 394, 574
Gajjar, V., Joshi, B. C., & Kramer, M. 2012, MNRAS, 424, 1197
Kaplan, D. L., Swiggum, J. K., Fichtenbauer, T. D. J., et al. 2018, ApJ , 855, 14
Ritchings, R. T. 1976, MNRAS, 176, 249
Stovall, K. et al. 2014, ApJ, 791, 67
Wang, N., Manchester, R. N., & Johnston, S. 2007, MNRAS, 377, 1383

The NANOGrav Physics Frontiers Center is supported by NSF award number 1430284. The Green Bank Observatory and National Radio Astronomy Observatory are facilities of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Arecibo Observatory is a facility of the National Science Foundation operated under cooperative agreement by the University of Central Florida in alliance with Yang Enterprises, Inc. and Universidad Metropolitana.

NANOGrav Physics Frontiers Center