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Nulling and Other Abnormal Pulsar Phenomena: Review and Analysis

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ABSTRACT

Nulling is a behavior exhibited by a significant number of radio pulsars whereby they skip pulse emission for one or several periods at a time. The mechanisms that cause this seemingly random cessation are not fully understood, and here I investigate some of the possible causes. There is no emergent relationship between a given pulsar's nulling tendencies and its characteristic parameters such as period, magnetic field strength, or energy output, though most explanations attribute the phenomenon to changes in the state of the neutron star's magnetosphere. This results in alterations to the geometry of the emission cone formed by the dipole field, which in turn affects how the pulses are observed on Earth (or whether they are at all). Though the exact mechanisms are yet unknown, the topic is an active area of ongoing research.

Keywords: pulsars: general — stars: statistics — catalogs — methods: data analysis

1. INTRODUCTION

Since the initial identification of radio pulsars as spinning neutron stars emitting sweeping beams of radiation in the late 1960s, a significant amount of research has gone into investigating the mechanisms behind their often perplexing behavior. Within just a few years of their discovery, a multitude of atypical pulsars had been observed, and many of the mysteries of their function remain unsolved to this day. *Nulling* is one such anomalous behavior, whereby a known pulsar ceases pulse emission for some number of periods where a pulse was expected. Since the phenomenon was first noted by Backer (1970), nearly 200 pulsars have been observed to exhibit nulling (Konar & Deka 2019). Despite this quantity, a definitive explanation for nulling remains elusive.

The parameters that are used to describe a pulsar's nulling behavior are the nulling fraction (NF)—the percentage of expected pulses missed—and the nulling length (NL)—the typical duration of a given null instance. Both of these numbers can vary widely, but there is no explicit relationship between either of these parameters and pulsars' other properties. As a visual representation of nulling, examples of varying degrees of pulse cessation are shown in Figure 1.

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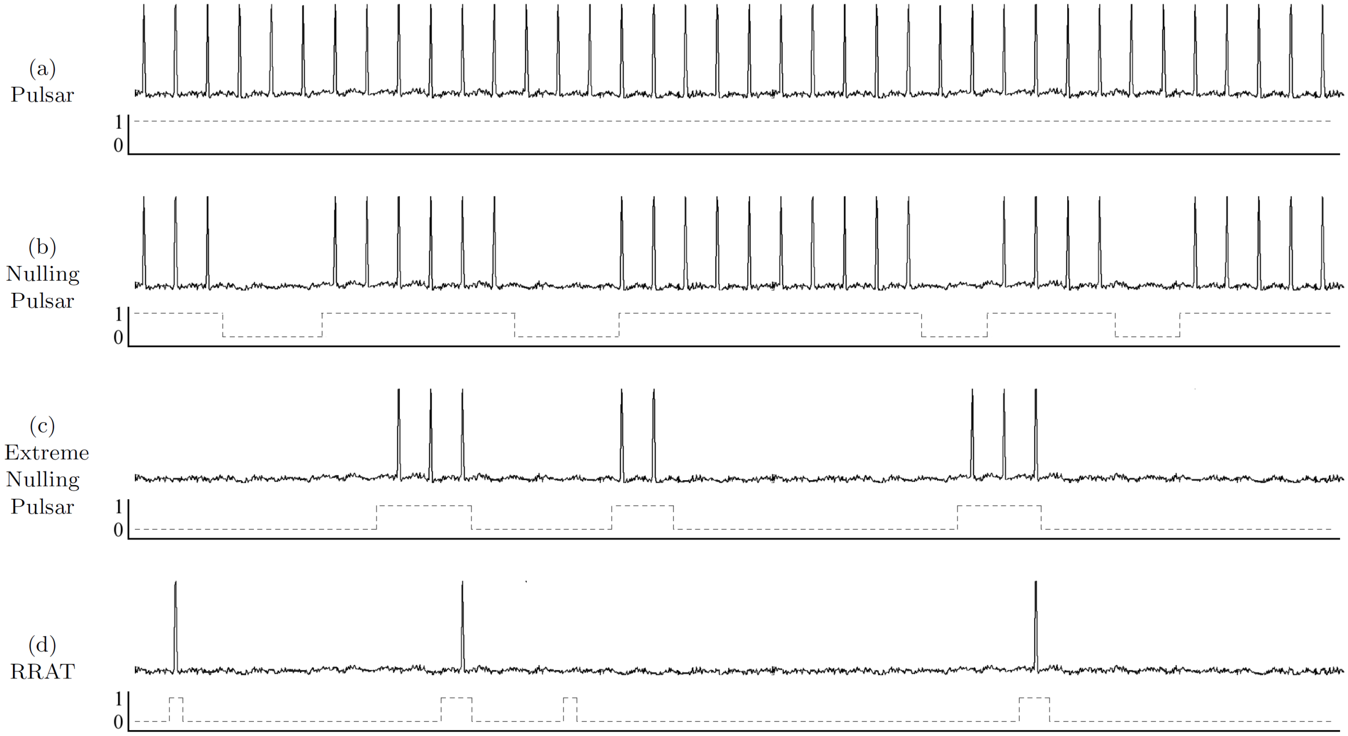


Figure 1. A normalized depiction of what it means to be a nulling pulsar, with increasingly large NF shown. An RRAT is a **r**otating **ra**dio **t**ransient, as described in McLaughlin et al. (2006), which are thought to be special nulling pulsars that only emit sporadically. Figure lifted from Burke-Spolaor & Bailes (2010) for example purposes.

2. OTHER ANOMALOUS BEHAVIOR

As for what causes pulsar nulling, it has been theorized to be possibly related to a number of other types of abnormal behavior that pulsars are known to exhibit. Some of the most notable are:

- Mode changing, described by Wang et al. (2007) as "another kind of discontinuous change where the mean pulse profile abruptly changes between two (or sometimes more) quasi-stable states."
- Glitching, where pulsars' rotation rates undergo "sudden increases ('glitches') followed by gradual recoveries" (Link et al. 1992).
- Drifting subpulses, or less prominent emission profiles with "second periodicities" (Drake & Craft 1968) that shift around relative to the major period.

2.1. *Mode Changing*

There is mounting evidence that mode changing and nulling are closely related, and may even be two manifestations of the same underlying phenomenon. Wang et al. (2007) found that two modes are often separated by a null episode and that nulling episodes are often followed by emission in a different mode when it picks back up. Redman & Rankin (2009) report that pulsars possess meaningfully different nulling properties from mode to mode. The relationship comes down to the geometry of the dipolar magnetic field that directs the emission outward from the NS. Given the proper sightline, we may observe emission or not based on the angle of the emission beam. This concept for how nulling and mode changing may be physically related is more readily depicted in Figure 2, from Timokhin (2010). Essentially the theory presented in this paper assumes emission directed along magnetic field lines and thus defines a beam opening angle,

$$\alpha = \theta + \arctan(B_\theta/B_r) \simeq 3\theta/2 \propto \theta_{\rm pc} \qquad (1)$$

where θ is the colatitude[1] of the emission zone ($\theta_{\rm pc}$ is that of the polar cap[2] specifically), and B is the magnetic field strength. It is clear that the magnetic field geometry directly affects the opening angle α under this model, and thus how focused the emission beam is.

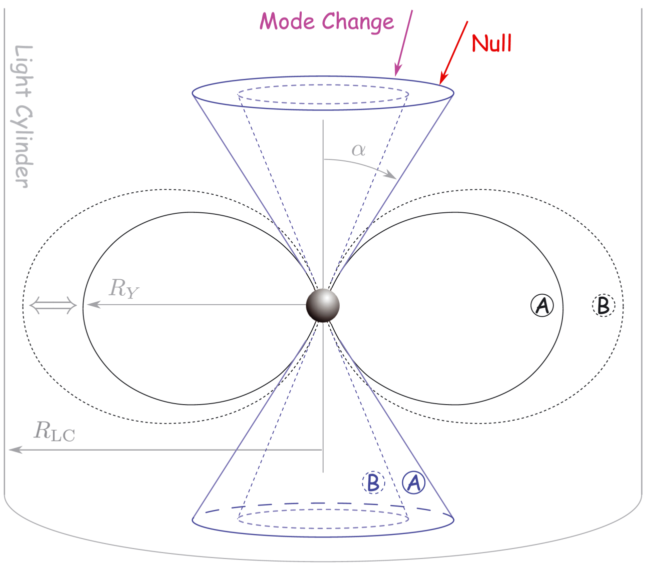


Figure 2. Shown here is the supposed relationship between mode changes and null intervals. The two arrows towards the top represent lines of sight from which one would observe one phenomenon versus the other. An observer looking from the red angle would no longer observe emission (a null) when the field changes state from Ⓐ to Ⓑ, while an observer at the purple arrow would now be subject to a more focused beam (a mode change). Even a small change in field geometry has a significant impact on α. Figure lifted from Timokhin (2010).

While Timokhin does not go so far as to propose exactly what may cause these mode switches that lead to observed nulls, the model does work well as an explanation for what is happening at the source.

2.2. *Glitching*

Glitches, on the other hand, are thought to be relatively unrelated to nulling. While Herfindal & Rankin (2007) noted that PSR B1136+16 displays a change in spin-down rate depending on its nulling state, this relationship has not been generalized and may not even be related to typical glitches, which Melatos & Peralta (2007) postulate are the result of differential rotation and turbulence in the neutron star's crust. They break down the glitching population by age and report that a K-S test on the Reynolds numbers[3] of pulsars with $\tau_c \geq 10^6$ versus those with $\tau_c \leq 10^6$ years reveals that the two distributions are statistically different. In Section 3, I take a similar approach to show that the age distribution of nulling vs. non-nulling pulsars does not differ in a significant way, which suggests that glitches and nulling are indeed the result of different underlying phenomena, given that they cluster differently in the same parameter space. While this is far from a complete treatment of pulsar glitching, it would be impossible to do full justice to the phenomenon here.

2.3. *Drifting Subpulses*

While radio pulsar emission is typically quite regular, it is not uncommon for there to be 'subpulses' in the profile—smaller, less intense peaks that occur in between the main radiation pulses. These subpulses are sometimes known to drift, a process that Gogoberidze et al. (2005) says "involves a pattern that drifts around the magnetic equator such that an individual subpulse reappears in the pulse window after a characteristic rotation time, P_3." The introduction of

[1] Colatitude is the complementary angle to a given latitude, i.e. colat $= 90° -$ lat

[2] For a dipolar field, $\theta_{\rm pc} \simeq \sqrt{R_{\rm NS}/R_Y}$, where R_Y is the radius of the corotating zone: the material around the NS that is caught up in the field.

[3] Re $= R^2\Omega/\nu_n$, where ν_n is the kinematic viscosity of the fluid. Glitching activity is proposed to be a function of the Reynolds number.

this separate period is physically explained by a 'carousel model' that invokes an array of periodically placed hypothetical columns of plasma that rotate around the magnetic axis of the NS. Whether or not they are in fact actual columns of plasma or just an artifact of a high-order multipole field has not been settled. Either way, the math to describe them is quite complicated and involves superpositions of spherical harmonic representations[4] of plasma, charge, and magnetic field distributions. The secondary period of the drifting subpulse ends up being given by

$$P_3 = 2\pi/\Delta, \text{ where } \Delta = \omega - n\Omega \tag{2}$$

where Δ represents a beat frequency between the rotational frequency of the NS (Ω) and the frequency of a 'drift wave' (ω), which is a product of the harmonics described above (n is simply an integer multiplier). This causes subpulse drifts to repeat with a frequency of P_3.

However, Filippenko & Radhakrishnan (1982) conclude that nulling does not have much to do with drifting subpulses anyway.

3. DATA ANALYSIS

In an attempt to discover some relationships between parameters for myself, I collected pulsar data from a number of sources and performed my own analysis in Python. An excerpt of the data I used is presented in Table 1, where its sources are also attributed. To start, I compared the nulling fraction to several of the most commonly used pulsar parameters, such as period, magnetic field strength, age ($\tau_c = {}^{P}/_{2\dot{P}}$), and energy loss rate. These plots are shown in Figure 3, where one can see that no obvious relationship immediately jumps out.

To rule out correlations statistically as well as visually, distribution tests can be performed to determine the likelihood that various samples were drawn from like distributions. For example, Figure 4 shows the normed distributions of the characteristic ages of nulling and non-nulling pulsars. Already they appear quite similar. And indeed, a K-S test reveals that the null hypothesis (that the two samples were drawn from the same distribution) cannot be rejected. This suggests that age is not a factor in influencing a pulsar's nulling behavior, as it was for glitching. Similar tests on other variables as well as attempts at regression all fail to produce any truly meaningful relationship.

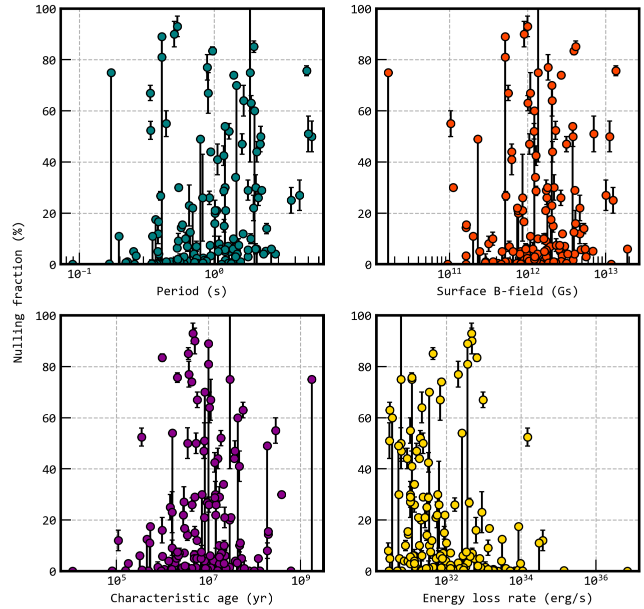


Figure 3. NF plotted against several of the classical pulsar parameters for the nulling pulsars reported in Konar & Deka (2019). Error bars/uncertainty margins were parsed from errors presented in the original data table, where nulling fractions given as upper limits are plotted with an error bar that spans the full range down to 0%, and so on.

A final visualization that I created—mostly out of curiosity—is the galaxy map shown in Figure 5. Using galactic x- and y-coordinates provided by the ATNF catalog (not to be confused with galactic latitude and longitude), I projected the locations into a polar space and scaled them to match the rendered map of the galaxy. As with other parameters that were

[4] i.e., instances of the Laplace harmonic function $Y_l^m(\theta, \varphi)$ where θ is again the colatitude and φ is the longitude.

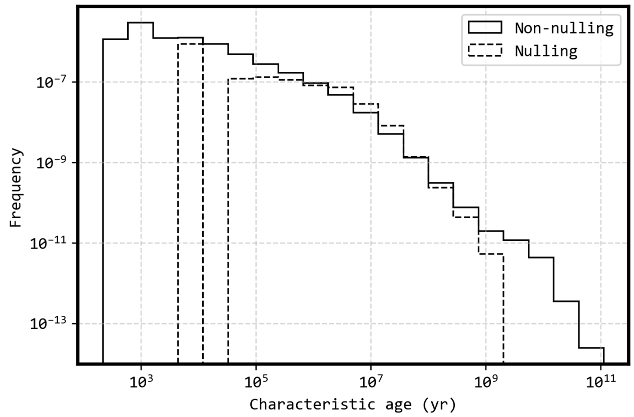


Figure 4. Density histograms of τ_c for nulling and non-nulling pulsars. Nulling pulsars appear here to be little more than just a subset of the larger population, with a distribution shape that is nearly identical.

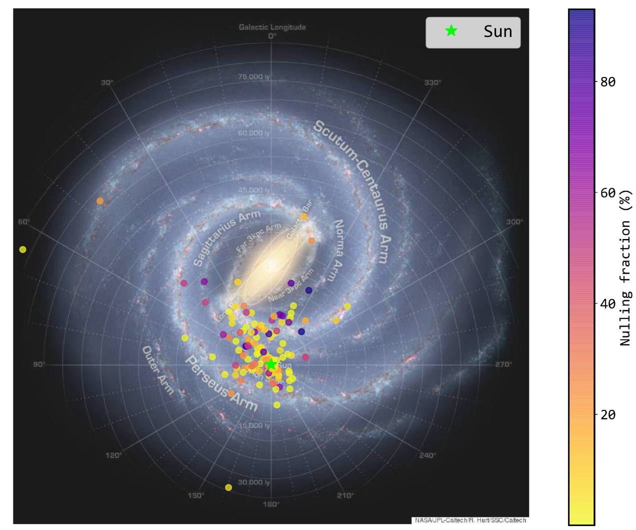


Figure 5. Plot of known nulling pulsars in the galactic plane overlaid on a rendered map of the Milky Way. This plot demonstrates two interesting features, which make sense upon reflection: the fact that the other side of the galaxy is mostly obscured by the galactic core, and that sources indeed seem to cluster within the arms. In general, the points can be assumed to lie within a few kpc of the galactic plane in the Z-direction. Background image credit NASA/JPL-Caltech/R. Hurt (SSC/Caltech), ssc2008-10b.

analyzed, there is no emergent relationship between pulsars' locations and their NF.

Although somewhat disappointing, it comes as no surprise that I was unable to establish any empirical relationship between nulling fraction and other pulsar parameters, given that the research community has been seeking to do so for years and cannot be said to have yet succeeded.

4. CONCLUSIONS

The true underlying cause of pulsar nulling remains a mystery. By some accounts, it cannot even be definitively said whether or not nullling in general is even a random phenomenon in the first place (Redman & Rankin 2008). Though there have been workable explanations proposed for what causes nulling, even these lack an explanation for the basic physics that causes the model to function in the way that it does.

To progress our knowledge of this phenomenon beyond what we know now, there are several important areas of research that should be further explored:

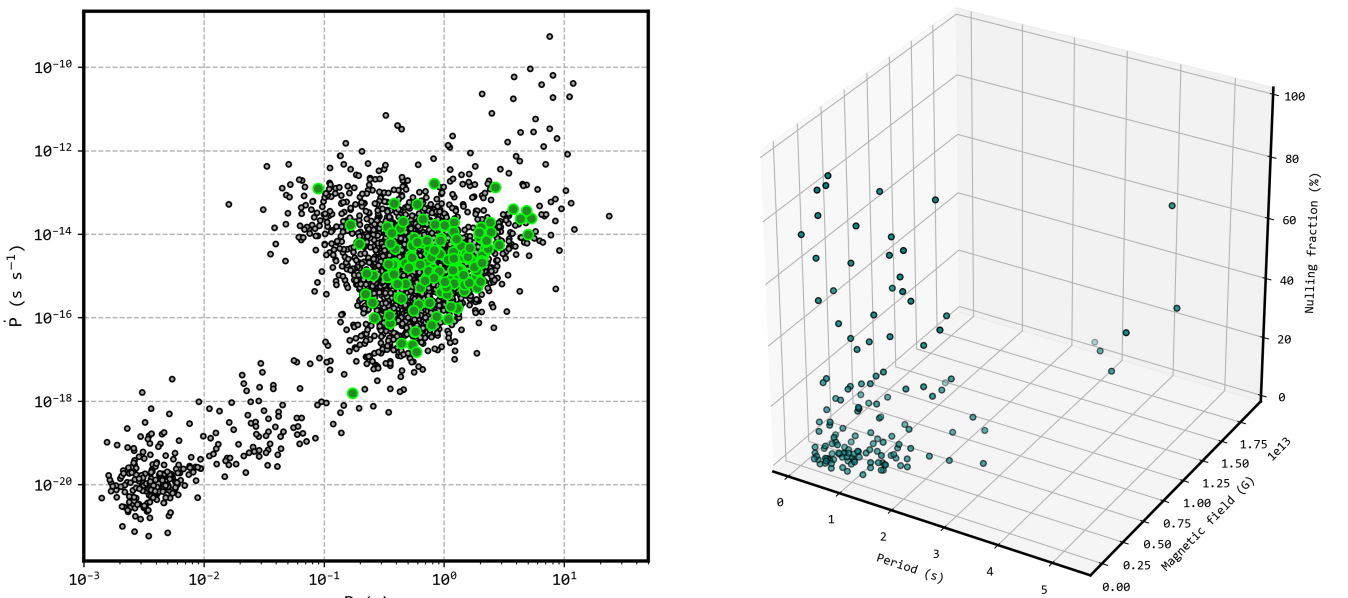
- Continued observation of nulling pulsars with emphasis on pulse profile morphology
- Collection and comparison of multi-wavelength spectra of mode changing pulsars in different states
- More advanced computational simulations of emission mechanisms that account for the anomalies discussed here

With more data in these areas, it will hopefully be possible to develop a physically motivated model that explains pulsar nulling from first principles up. Only once we have a explanation that is complete, widely compatible with observations, and physically feasible can we be truly said to have discovered the nature of nulling.

Software: Python, pandas, SciPy, Matplotlib, astropy. *The full source code I wrote for analysis and plot generation is available*[7] *as an interactive Jupyter notebook with commentary.*

APPENDIX

A. ADDITIONAL PLOTS



(a) (b)

Figure 6. **(a)** is a typical P-$\dot{P}$ diagram showing period versus spin-down rate with nulling pulsars highlighted in green. They do not really cluster or display any obvious trend beyond merely the fact that they all reside among the main population. **(b)** essentially combines two of the plots from Figure 3 and plots NF as a multivariate function of both period and magnetic field strength in an attempt to see if there is a trend when looked at in three dimensions. Some clustering is apparent but nothing with predictive capability.

B. CONSOLIDATED DATA

Table 1 is an excerpt of a data table of relevant information on pulsars that exhibit both nulling and glitching behavior. General parameter data was sourced from the ATNF pulsar catalog[5] (Manchester et al. 2005), nulling data from Konar & Deka (2019), and glitch data from the Jodrell Bank Center for Astrophysics' glitch table[6] (Espinoza et al. 2011). Errors/uncertainty have been omitted from this table to save space, but were factored into the analysis and are available digitally in the GitHub repository previously mentioned in the software credits.[7]

[5] http://www.atnf.csiro.au/research/pulsar/psrcat
[6] http://www.jb.man.ac.uk/pulsar/glitches.html
[7] https://github.com/cgobat/pulsar-nulling

Table 1.

PSRJ (name)	P (s)	$\dot{P}$ ($s \cdot s^{-1}$)	DM ($cm^{-3} \cdot pc$)	Distance (kpc)	Age (years)	B-field (Gauss)	$\dot{E}$ (erg/s)	NF (%)	Glitches (num)	$\Delta\nu$ (%)	$\Delta\dot{\nu}$ (%)
J0525+1115	0.3544	7.36E-17	79.418	1.84	7.63E+07	1.63E+11	6.50E+31	0.06		2.70E-19	
J0528+2200	3.7455	4.01E-14	50.8695	1.22	1.48E+06	1.24E+13	3.00E+31	25	3	1.90E-18	1.30E-05
J0659+1414	0.3849	5.49E-14	13.94	0.29	1.11E+05	4.65E+12	3.80E+34	12	2	6.00E-19	3.00E-07
J0742-2822	0.1668	1.68E-14	73.728	2	1.57E+05	1.69E+12	1.40E+35	0.2	8	1.20E-18	-8.00E-07
J0835-4510	0.0893	1.25E-13	67.97	0.28	1.13E+04	3.38E+12	6.90E+36	0.0008	19	2.34E-15	1.00E-05
J0922+0638	0.4306	1.37E-14	27.2986	1.1	4.97E+05	2.46E+12	6.80E+33	0.05	1	1.26E-15	
J1509+5531	0.7397	5.00E-15	19.6191	2.1	2.34E+06	1.95E+12	4.90E+32	7	1	2.00E-19	-6.00E-06
J1532+2745	1.1248	7.80E-16	14.691	1.69	2.29E+07	9.48E+11	2.20E+31	6	1	2.90E-19	-1.00E-06
J1644-4559	0.4551	2.01E-14	478.8	4.5	3.59E+05	3.06E+12	8.40E+33	0.4	3	1.91E-16	2.00E-06
J1709-1640	0.6531	6.31E-15	24.891	0.56	1.64E+06	2.05E+12	8.90E+32	23		3.73E-19	0
J1731-4744	0.8298	1.64E-13	123.056	0.7	8.04E+04	1.18E+13	1.10E+34	0.1	7	1.37E-16	1.50E-06
J1801-0357	0.9215	3.31E-15	120.37	5.74	4.41E+06	1.77E+12	1.70E+32	26	1	3.10E-18	2.00E-06
J1812-1718	1.2054	1.91E-14	255.1	3.68	1.00E+06	4.85E+12	4.30E+32	5.8	3	1.50E-18	6.00E-06
J1847-0402	0.5978	5.17E-14	141.979	3.42	1.83E+05	5.63E+12	9.60E+33	3		4.50E-19	8.00E-08
J1910+0358	2.3303	4.47E-15	82.93	2.86	8.26E+06	3.27E+12	1.40E+31	4	1	1.30E-18	9.00E-06
J1919+0021	1.2723	7.67E-15	90.315	5.88	2.63E+06	3.16E+12	1.50E+32	0.4	1	1.90E-18	1.00E-05
J1926+0431	1.0741	2.46E-15	102.243	4.99	6.92E+06	1.64E+12	7.80E+31	5	1	8.00E-20	-2.00E-07
J2022+2854	0.3434	1.89E-15	24.63109	2.1	2.87E+06	8.16E+11	1.80E+33	0.2		1.30E-19	5.00E-07
J2116+1414	0.4402	2.89E-16	56.2044	25	2.41E+07	3.61E+11	1.30E+32	1	1	2.60E-19	8.00E-06
J2219+4754	0.5385	2.77E-15	43.4975	2.39	3.09E+06	1.23E+12	7.00E+32	2		1.14E-18	1.00E-06
J2346-0609	1.1815	1.36E-15	22.504	3.7	1.37E+07	1.28E+12	3.30E+31	42.5		5.99E-19	2.12E-06

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