A Method to Assess the Applicability and Accuracy of the Modified Gaussian Model (MGM) on the Rock Samples' Spectral Interpretation (Postprint)

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Abstract

The Chang' e-4 mission obtained spectral data from multiple rock targets on the lunar surface. While the Modified Gaussian Model (MGM) is commonly applied to the spectral interpretation of powder samples, its applicability and accuracy for rock targets remain to be further evaluated. This study utilizes a rock slice of the lunar meteorite NWA 4734 to conduct a comprehensive analysis of petrography, mineralogy, and laboratory spectroscopy, providing important ground truth for MGM interpretation of lunar in situ rock sample spectra. First, scanning electron microscope (SEM), Energy Dispersive Spectrometer (EDS), and Electron Probe Micro-Analyzer (EPMA) analysis results indicate that: (1) almost all plagioclase in NWA 4734 has been converted to maskelynite, indicating that the meteorite has experienced severe impact metamorphism; (2) the chemical composition of pyroxene and olivine is significantly heterogeneous, exhibiting a distribution characteristic of magnesium-rich cores and iron-rich rims, further suggesting that NWA 4734 has undergone multiple episodes of crystallization and differentiation. Second, this study focuses on the Backscattered Electron (BSE) greyscale image of the NWA 4734 rock slice and determines the proportion of High-Calcium Pyroxene (HCP) relative to total pyroxenes in this sample by calculating area percentages using a pixel counting method. The results show that the HCP proportion is 72% ± 5.4%, which can serve as ground truth for evaluating the applicability and accuracy of MGM interpretation. A field spectrometer (ASD) is employed to measure the visible and near-infrared reflectance spectra (450–2500 nm) of the NWA 4734 rock slice in the same region where the BSE image was obtained via SEM. MGM is then used to deconvolve the ASD spectra, yielding an estimated average HCP proportion of 71% ± 10.1%. The results from MGM and pixel counting are comparable within error ranges, demonstrating the applicability of MGM for interpreting rock samples on the

lunar surface.

Full Text

Preamble

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Statistical Research on Megahertz-peaked Spectra Pulsars

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Abstract

Megahertz-peaked spectra (MPS) pulsars are defined as those whose radio spectra turn over around 100 MHz. We identified 53 MPS pulsars based on spectral data from the literature and statistically analyzed their spatial distribution, magnetic field-period distribution, peak frequencies, spectral indices, and dispersion measures. We found a strong positive correlation between the dispersion measures and peak frequencies of MPS pulsars, along with negative correlations between dispersion measures and both spectral indices and ages. These correlations suggest that the interstellar medium is an important factor affecting the observational properties of MPS pulsars.

Key words: (stars:) pulsars: general –radio continuum: general –ISM: general

1. Introduction

Radio spectra of pulsars provide important information about pulsar radiation mechanisms. Sieber (1973) studied the radio spectra of 27 pulsars and found that most could be described by a simple power-law spectrum: $S_\nu = S_0\nu^\alpha$, where S_ν is the flux density at frequency ν, S_0 is the flux density at 1 GHz, and α is the spectral index, which is generally negative. Sieber (1973) also identified a class of pulsars with inverted spectral shapes, with spectral peaks near several hundred megahertz. In this paper, we refer to such low-frequency inverted-spectrum pulsars as megahertz-peaked spectra (MPS) pulsars.

To investigate the physical mechanisms behind MPS pulsars, Sieber (1973) attempted to fit the low-frequency inversion using both the synchrotron self-absorption (SSA) model and the free-free absorption (FFA) model. According to Kellermann (1966), when the brightness temperature of synchrotron radiation from electrons in a magnetic field approaches the kinetic temperature of the electrons, the electrons' self-absorption becomes non-negligible, a phenomenon known as SSA. For pulsars, SSA processes occur within the magnetosphere. FFA, in contrast, arises from cold electrons between the emission source and the observer absorbing passing radiation, and thus typically occurs outside the pulsar, with the interstellar medium being the primary location for FFA.

Marcote et al. (2015) applied SSA, FFA, and SSA plus Razin effect models to fit the low-frequency inverted spectrum of LS 5039, finding that SSA plus the Razin effect provided a better match than SSA or FFA alone. Jankowski et al. (2018) identified 10 pulsars with inverted phenomena in the 50–100 MHz frequency range and speculated that FFA processes in the interstellar medium surrounding the pulsar caused the inverted spectra. Cong et al. (2021) constructed FFA maps using a cylindrical emissivity model and the NE2001 free electron distribution model, showing that the interstellar medium undergoes more drastic FFA in low-frequency bands.

Research has also examined whether low-frequency inversion phenomena exist in millisecond pulsars. Kuzmin & Losovsky (2001) studied the radiation spectra of 30 millisecond pulsars in the 102–111 MHz band and found that most did not exhibit inversion behavior, with only PSR J1012+5307 possibly having an inverted spectrum near 100 MHz. They suggested that the absence of low-frequency inversion in most millisecond pulsars might be related to differences in the structure of their emission regions compared to normal pulsars. According to Kuzmin & Losovsky (2001), millisecond pulsars have smaller light cylinders, which may alter the magnetic field configuration from pure dipole to multipole. The small divergence in multipole fields can suppress the appearance of low-frequency turnover. In fact, the magnetic configuration of millisecond pulsars after accretion is complex, and local strong magnetic zones may exist due to accretion-induced magnetic redistribution (e.g., Zhang & Kojima 2006).

More recent studies have investigated low-frequency inversion phenomena in millisecond pulsars (e.g., Kuniyoshi et al. 2015; Wang et al. 2021; Lee et al. 2022). In particular, Wang et al. (2021) discovered the millisecond pulsar J0318+0253, which has the weakest radio flux ever recorded, with a peak inversion frequency near 350 MHz. They suggested that inversion phenomena in millisecond pulsars may be related to intrinsic properties of the pulsars themselves.

2. Fitting Model for MPS Pulsar Spectra

When electrons collide with ions, they not only emit photons through free-free radiation but may also absorb photons, causing free electrons to transition from lower to higher kinetic energy states. This inverse process of free-free radiation is known as FFA. Lewandowski et al. (2015) found that the effect of FFA on pulsar radiation spectra depends on the size of the absorption region, electron density, and electron temperature, with FFA being particularly sensitive to changes in electron density. Kijak et al. (2017) studied high-frequency inverted spectra of pulsars using the FFA model; these high-frequency inverted-spectrum pulsars are also called gigahertz-peaked spectra (GPS) pulsars. Existing research has shown that the FFA model can accurately describe GPS spectra, so we also use the FFA model to explain low-frequency inversion phenomena in MPS pulsars.

In this paper, we adopt the formula from Swainston et al. (2022) to fit pulsar spectra. The specific form is given by Equation (1), where the reference frequency ν_0 is the geometric mean of the minimum and maximum frequencies, α is the spectral index, ν_{peak} is the peak frequency, and c is a constant. Here α, ν_{peak}, and c are the parameters to be fitted.

We adopt the method proposed by Jankowski et al. (2018) to minimize systematic errors introduced by different telescopes when measuring flux densities. To reduce the negative impact of outliers during fitting, this method utilizes the Huber loss function to handle flux density error outliers, as expressed by:

$$\mathcal{L}(y_i, f_i) = \begin{cases} \frac{1}{2}\left(\frac{y_i - f_i}{\sigma_{y,i}}\right)^2 & \text{if } \left|\frac{y_i - f_i}{\sigma_{y,i}}\right| \leq k \\ k\left|\frac{y_i - f_i}{\sigma_{y,i}}\right| - \frac{1}{2}k^2 & \text{otherwise} \end{cases}$$

where f_i is the model predictive value, y_i is the actual observation, $\sigma_{y,i}$ is the flux density error value, and k defines the distance at which the loss function begins to penalize outliers. In this work, we choose $k = 1.345$ as the threshold for outliers. According to Huber (1964), when $|y_i - f_i|/\sigma_{y,i}$ is less than 1.345, the data point is considered normal; when it is greater than or equal to 1.345, it is considered an outlier. See Swainston et al. (2022) for details on this model-fitting method.

3. Statistical Analysis of MPS Pulsars

We compiled 69 pulsars previously considered to have low-frequency inversion spectra from the literature, as detailed in Table 1, where DM is the dispersion measure, T_c is the characteristic age, P is the period, $\dot{P}$ is the period derivative, and B is the pulsar surface magnetic field. These parameters are all from the Australia Telescope National Facility (ATNF) Pulsar Catalogue (Manchester et al. 2005). The spectral index α_0 and peak frequency ν_{peak} are from the references in column 9. Millisecond pulsars in Table 1 are marked with asterisks.

To further inspect the spectral shapes of the pulsars in Table 1, we supplemented them with new spectral data from the pulsar_{spectra} software library (Swainston et al. 2022) and refitted the spectra using Equation (1). Based on the new spectral shapes and fitting results, we found that only 44 pulsars in Table 1 have definite inversion spectra, as shown in Table 2. In Figure 1 [Figure 1: see original paper], we present the fit for PSR J0809-4753, while fitting results for other MPS pulsars are shown in Appendix A. The α and ν_{peak} values in Table 2 are newly fitted results from Equation (1).

Before fitting, we prejudge the spectral trend. Data points far from the spectral trend may be regarded as outliers. During fitting, we prioritize ensuring that data points near 1 GHz conform to the turn-up or power-law spectral model because spectral flattening phenomena generally appear in higher-frequency bands (Maron et al. 2000). We also prioritize data points from interferometric imaging observations, which are less affected by scattering. For example, Murphy et al. (2017) provided interferometric imaging observations for PSR J0820-1350, and we prioritize fitting these data. However, in some cases it is difficult to judge which points are outliers, especially at low frequencies due to scarce data coverage. For instance, it is difficult to determine which point is an outlier near 100 MHz for PSR J2354+1655; this can only be resolved through future observations. The spectral parameters in Table 2 may differ from those in Table 1 due to the inclusion of the latest data in our fitting.

During our literature review of MPS pulsars, we also found nine pulsars with spectral breaks that actually exhibit inversion characteristics. These pulsars were also fitted using the FFA model, with results shown in Table 3 and Figure 2 [Figure 2: see original paper]; α_0 values are from the references in Table 3. These pulsars were categorized as spectrally broken pulsars by Bilous et al. (2016) and Murphy et al. (2017).

Based on the statistical results in Tables 2 and 3, we obtained a total of 53 MPS pulsars. In the following sections, we carry out a statistical analysis of these MPS pulsars.

3.1. MPS Pulsars Spatial Distribution

We show the spatial distribution of the 53 MPS pulsars in Galactic coordinates in Figure 3 [Figure 3: see original paper]. The figure reveals that most MPS pulsars are distributed in low Galactic latitude regions. Figure 4 [Figure 4: see original paper] displays the projected distribution of these pulsars on the Galactic plane, where the horizontal and vertical coordinates are the Galactic plane coordinate components X and Y, respectively, with the Galactic center at (0, 0) and the Sun at (0, 8.5 kpc) (Kerr & Lynden-Bell 1986).

We depict the statistical distribution of distances of the 53 MPS pulsars from the Galactic center in Figure 5 [Figure 5: see original paper]. The figure shows that most MPS pulsars tend to be distributed on one side of the solar system, similar to other normal radio pulsars (Xu et al. 2011), with a mean distance from the Galactic center of 8.31 kpc. The distribution is well-characterized by a Gaussian distribution peaking around 8.74 kpc. This phenomenon may be due to observational selection effects, including interstellar dispersion and scattering (Xu et al. 2011).

3.2. B-P Distribution of MPS Pulsars

Using data from the ATNF Pulsar Catalogue (Manchester et al. 2005), we plot the magnetic field-period (B-P) distributions of the 53 MPS pulsars in Figure 6 [Figure 6: see original paper]. Except for two millisecond pulsars, the 51 MPS pulsars have an average magnetic field strength of 1.75×10^{12} G and an average rotation period of 0.95 s. Figure 6 shows that five MPS pulsars (including the two millisecond pulsars) are located between the spin-up line (Bhattacharya & van den Heuvel 1991) and the death line (Taylor & Stinebring 1986). These five pulsars have an average DM of 12 pc cm^{-3}, while the remaining 48 MPS pulsars have an average DM of 57 pc cm^{-3}. This suggests that MPS pulsars located between the spin-up and death lines likely have lower DMs than other MPS pulsars.

3.3. Peak Frequency Statistics of MPS Pulsars

The peak frequency distribution of the 53 MPS pulsars is shown in Figure 7 [Figure 7: see original paper]. The average peak frequency is 0.12 GHz. The figure reveals that the peak frequencies of 48 MPS pulsars (91% of the total) are distributed below 0.20 GHz. We further performed a statistical analysis of correlations between the peak frequencies of MPS pulsars and other parameters. The analysis shows that the peak frequency ν_{peak} is weakly correlated with characteristic age T_c, with a Pearson correlation coefficient of -0.19. Additionally, while Izvekova et al. (1981) suggested a correlation between ν_{peak} and period P for MPS pulsars, we do not find a significant correlation between ν_{peak} and P in our sample. This potential correlation requires further observational verification.

3.4. Spectral Index Distribution of MPS Pulsars

Figure 8 [Figure 8: see original paper] shows the spectral index distribution of MPS pulsars, with an average spectral index of -1.85. PSR J1913-0440 has the steepest spectral index (-2.80), while PSR J1321+8323 has the flattest (-0.69). We obtained a spectral index of -1.98 for J1614+0737, which is flatter than the -3.80 value determined by Malofeev et al. (1994). This difference may be due to the small number of available data points in the earlier study.

According to Tables 1 and 3, the average spectral index of the 53 MPS pulsars reported by previous authors was -2.23. In this paper, due to the addition of new spectral data, the average spectral index obtained from FFA model fitting is -1.85, which is flatter than previous results. Jankowski et al. (2018) suggested that the gradual flattening of pulsar spectral indices may be a trend that could strengthen with further observations at both low and high frequencies. We also investigated the correlation between the distance $|z|$ of MPS pulsars from the Galactic plane and their spectral indices but found no significant correlation.

3.5. DM Distribution

The DM distribution of the 53 MPS pulsars is shown in Figure 9 [Figure 9: see original paper], with a mean DM of 53 pc cm^{-3}. The figure shows that 38 MPS pulsars (72% of the total) have DMs between 0 and 50 pc cm^{-3}. For comparison, we calculated the average DM of 3267 pulsars in the ATNF Pulsar Catalogue (Manchester et al. 2005), which is 204 pc cm^{-3}—much higher than that of MPS pulsars. The lower average DM of MPS pulsars is obviously due to selection effects: many pulsars with higher DMs are completely scattered at low frequencies, making flux density measurements unavailable.

4. Discussion

Through fitting and analysis of available spectral data, we identified that 44 pulsars in Table 1 exhibit low-frequency inversions. Although the remaining 25 pulsars in Table 1 were previously thought to have low-frequency inversions, they do not show significant inversion phenomena based on newly published spectral observations. We present fitting results for these 25 pulsars using a power-law model in Appendix B.

For comparison with MPS pulsars, we also statistically analyzed parameters of all pulsars from the ATNF Pulsar Catalogue (Manchester et al. 2005). The average age of MPS pulsars is 2.8×10^5 kyr, which is younger than the 1.7×10^6 kyr average for the ATNF catalogue. The average period derivative of MPS pulsars is 5.22×10^{-15} s s^{-1}, smaller than the 4.03×10^{-13} s s^{-1} average for the ATNF catalogue. Additionally, the mean distance of MPS pulsars (from Earth) is 1.86 kpc, much smaller than the 6.04 kpc average for the ATNF catalogue. We attribute the smaller distances of MPS pulsars to observational selection effects: identification of spectral inversion relies heavily on low-frequency observations, but low-frequency pulsar observations are severely affected by dispersion and scattering, so only nearby pulsars have available low-frequency data and can be identified as MPS pulsars.

Lorimer et al. (1995) studied 343 pulsars and explored correlations between spectral indices α and parameters such as P, $\dot{P}$, T_c, B, and rotational energy loss rate $\dot{E}$. They found relatively strong correlations between spectral index and characteristic age, but no significant correlations between spectral index and period, period derivative, characteristic age, or other parameters. We also analyzed correlations between the spectral indices of MPS pulsars and other parameters, finding no significant correlations between spectral indices and periods, period derivatives, or characteristic ages.

However, we found a relatively strong correlation between DM and spectral index, with a correlation coefficient of −0.47, as shown in Figure 10 [Figure 10: see original paper]. This correlation may be an observational selection effect: greater DM requires stronger radio emission at low frequencies for detection, resulting in steeper spectral indices. We further explored correlations of MPS pulsars' DMs with their peak frequencies and ages (see Figure 10), obtaining correlation coefficients of 0.67 and -0.45, respectively. The strong correlation between DMs and peak frequencies indicates that low-frequency inversion is related to the interstellar medium, suggesting that FFA from the interstellar medium may cause low-frequency inversion. The correlation between DMs and ages suggests that the interstellar medium is an important factor influencing the evolution of MPS pulsars.

To better understand the nature of MPS pulsars, we compared them with GPS pulsars. Kijak et al. (2021) listed 33 GPS pulsars discovered to date. GPS pulsars are generally young, with 27 of 33 having ages less than 10^3 kyr, whereas MPS pulsars are older, with an average age of 2.8×10^5 kyr. The mean spectral index of MPS pulsars is -1.85, while GPS pulsars are flatter, with a mean spectral index of -1.46. The average DM of MPS pulsars is 53 pc cm^{-3}, whereas the mean DM of GPS pulsars is as high as 346 pc cm^{-3}—much larger than that of MPS pulsars.

We further explored correlation coefficients between DMs and spectral indices, peak frequencies, and ages for GPS pulsars, obtaining values of -0.05, 0.50, and -0.35, respectively. The corresponding correlation coefficients for MPS pulsars are -0.47, 0.67, and -0.45, respectively, indicating that DM has a more significant effect on MPS pulsars.

Low-frequency data are crucial for determining the turnover characteristics of pulsar spectra but are vulnerable to scattering. To estimate scattering effects on MPS pulsar data at the lowest frequencies, we calculated pulse-broadening times τ_d according to Bhat et al. (2004) and obtained the ratio of pulse-broadening time to pulsar period, τ_d/P. We found that only four pulsars—J1836-1008, J1829-1751, J0809-4753, and J2257+5909—have ratios greater than 1 at the lowest frequencies in their spectra, with values of 12.01, 2.9, 2.15, and 1.64, respectively. Although the first three pulsars have large τ_d/P ratios, indicating significant pulse smearing from scattering, the lowest frequencies adopted in this paper come from interferometric imaging observations, which are less affected by scattering. PSR J2257+5909 has $\tau_d/P = 1.64$ at 102 MHz, and its flux density at 102 MHz was measured through pulse profile measurements, which may have large errors due to scattering. Overall, the low-frequency data for 52 of the 53 MPS pulsars are less affected by scattering; the turnover characteristic of PSR J2257+5909 requires confirmation through future low-frequency observations.

5. Conclusion

We identified 53 pulsars with low-frequency inversion characteristics by fitting and analyzing available multi-band pulsar data. We statistically studied the spatial positions, B-P distribution, peak frequencies, spectral indices, and DMs of these 53 MPS pulsars. Compared with corresponding average values from the ATNF Pulsar Catalogue, MPS pulsars have smaller average characteristic ages, smaller average DMs, and smaller average distances from Earth. We find a strong correlation between spectral indices and DMs, indicating that DM may be an important factor affecting the spectral indices of MPS pulsars. We also find a strong positive correlation between DMs and peak frequencies and a negative correlation between DMs and ages. These results suggest that the interstellar medium is an important cause of low-frequency inversion spectra and demonstrate that FFA is an important mechanism for the low-frequency inversion of pulsars.

It is obvious that this sample is biased toward pulsars with small DMs because identification of MPS pulsars relies heavily on low-frequency observations, and pulsars with smaller DMs are easier to observe. Therefore, more low-frequency observations and larger MPS pulsar samples are needed to confirm these statistical results.

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Appendix A: The Fitting Spectra of 44 Identified MPS Pulsars in Table 1

[FIGURE:A1]

Appendix B: The Spectra of 25 Pulsars in Table 1 Without the Inversion Phenomena

[FIGURE:B1]

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