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PULSARS AS SPIRAL ARM TRACERS

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ABSTRACT

Pulsars are used to trace the spiral arms of the Galaxy. Present pulsar characteristics are used to divide them into two pulsar types as defined by Huang (1987). Those pulsars of Type II are believed to be the remnants of extreme Population I stars. The ages of Type II pulsars and the galactic rotation curve are used to determine their position at birth. The spiral arm pattern velocity is used to reconstruct the arms from which the individual Type II pulsars originated. It is found that the best fit to the data requires spiral arm segments with a pitch angle of 14°.5. The present Type II pulsar positions also indicate the same local pattern.

Key words: pulsars: galactic–Milky Way: structure

1. Introduction

The distribution of pulsars in the Galaxy has been used in the past to determine the pulsar birthrate and its correlation with the supernova rate (Taylor 1979; Lyne 1982; Lyne, Manchester, and Taylor 1985). These studies have relied on the large amount of data gathered by various radio searches for pulsars summarized by Manchester (1987) and Lyne *et al.* (1985). The most complete catalog of pulsar parameters, including position, periods, period derivatives, and dispersion measures, was published by Manchester and Taylor in 1981 (MT hereafter). This catalog has been the data source for studies of the distribution of pulsars in both the galactic disk and at heights above and below the disk. While most pulsar studies have been concerned with the pulsar birthrate and galactic distribution, only a few have considered using pulsars as a tracer of spiral structure (Amnuel, Guseinov, and Rustamov 1986; del Romero and Gómez-González 1981). Taylor (1979) noted in passing the "clumping" of pulsars at longitudes of 180°, 310°, and 330° indicating spiral structure. Blaauw (1985) recommends using pulsars between the ages of 20 and 50 million years as spiral arm tracers since, even with large velocities at birth, these objects could not move far from their "birthplace". In most cases data are either distance or age limited to show only the local distribution of pulsars and their association with star-forming regions (Amnuel *et al.* 1986).

A complete study using the available data is presented here. The suitability of pulsars as spiral arm tracers will be examined and the results will be compared to those of more conventional objects such as H II regions, OB associations, and molecular clouds. The major difficulties that have to be addressed are age determination and space velocities of pulsars. Recent theories of pulsar characteristics lead to the possibility of the existence of two distinct pulsar types (Huang 1987). One of these types would have originated from Type I supernovae (i.e., white-dwarf progenitor surpassing its mass limit) and the other from Type II supernovae (i.e., the detonation of massive Population I stars). The characteristics of the two pulsar types can be used as a criterion for distinguishing them.

2. Method of Analysis

2.1 *Distances*

Data from MT, Guseinov and Yusifov (1984), Clifton and Lyne (1986), Stokes *et al.* (1986), and Dewey *et al.* (1988) are used to determine the distances to the individual pulsars and their galactocentric distances. The relation between dispersion measure and distance can be utilized to determine the distances to pulsars if an electron density for the Galaxy is assumed. The following relation for the electron density from MT and Lyne *et al.* (1985) was adopted,

$$n_e = \left[0.025 + 0.015 \exp\left(-\frac{|z|}{70} \right) \right] \left[\frac{2}{1 + R/R_\odot} \right] , \quad (1)$$

where $|z|$ is the scale height in parsecs, R is the pulsar galactocentric distance in kiloparsecs, and $R_\odot$ is the Sun's galactocentric distance. The value $R_\odot = 8.5$ kpc is used here. Equation (1) is valid for most pulsars with the exception of those located behind the Gum nebula and those with distances determined by different means (see Table III, MT). These individual pulsars are given the values adopted by MT. The distance to the pulsars, d, and their galactic coordinates are used to determine (R, θ), the galactic cylindrical coordinates of the individual pulsars. The present positions of 422 pulsars are shown in Figure 1 in a $\log R, \theta$ plot. The Sun is at $\log R = 3.93$, $\theta = 360°$. Such plots are useful for tracing spiral structure

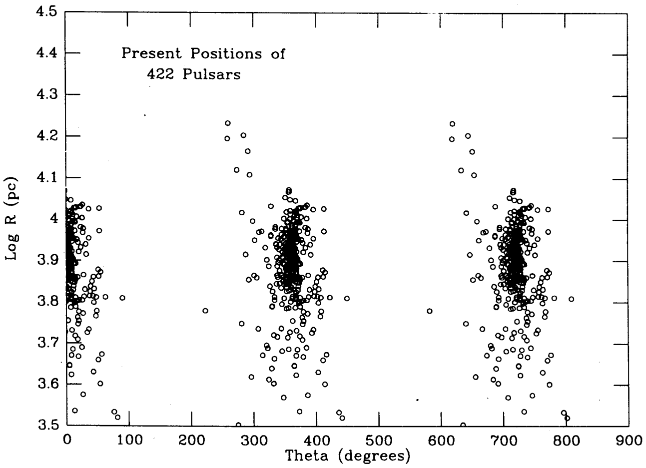

FIG. 1–The present positions of 422 pulsars in a log R,θ diagram, where R and θ are the galactocentric cylindrical coordinates. The Sun is at log $R = 3.93$, $\theta = 360°$.

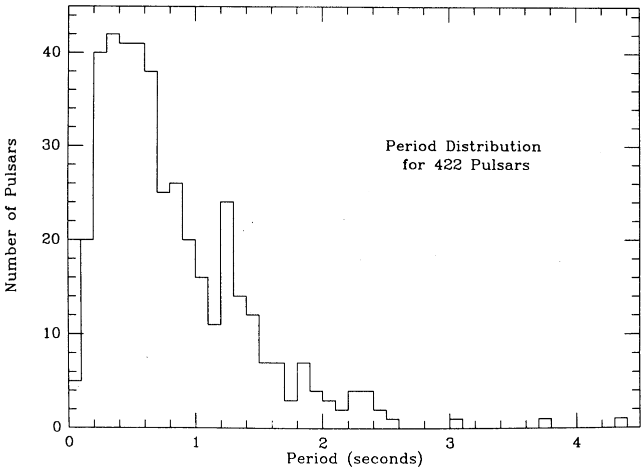

FIG. 2–The period distribution of 422 pulsars. The excess of pulsars with periods between 1.2 and 1.4 seconds is thought to be due to the limiting maximum period of 1.3 seconds for Type II pulsars.

(Elmegreen 1985) since logarithmic spirals will appear as straight lines.

2.2 *Pulsar Types*

Pulsars have been known to exist for only about 20 years. Their characteristics are still being explored, particularly how they form, what their attributes were at formation, and how they evolve. The idea that pulsars can come in distinct varieties is not a new one. Their $|z|$ distribution, beaming mechanisms, and periods have in the past been used as criteria to differentiate pulsar types (Manchester and Taylor 1977; Helfand and Tademaru 1977). Recently, Huang, Huang, and Peng (1985) have investigated the possibility of two types of pulsars originating from the corresponding supernovae types. Basic properties of the two types are distinct, such as the $P - \dot{P}$ relations, magnetic-field strengths, equations of state, size, emission mechanisms, and space velocity (see Huang 1987). The criteria for distinguishing the two types of pulsars are the spindown rate-period relation and the magnetic-field strength at formation (Huang *et al.* 1985).

Figure 2 shows the distribution of periods for 422 pulsars. There is an unusually large number with periods between 1.2 and 1.4 seconds, contrary to the premise that as pulsars slow down their luminosities decrease making them harder to detect. Huang *et al.* (1985) have shown that some pulsars tend to slow down to a maximum period, P_∞, of about 1.3 seconds. These pulsars have spin-down rates given by $\dot{P} \propto P^{-1}$. Other pulsars follow a spin-down rate of $\dot{P} \propto P^2$. Unlike the first type there is not a maximum period that these pulsars tend toward. This difference is used as a criterion to distinguish the pulsar types. Pulsars that follow the $\dot{P} \propto P^{-1}$ are considered to be Type II pulsars, while those that follow the $\dot{P} \propto P^2$ are Type I. As previously stated the pulsar types are analogous to the supernova types which produced them. The different formation scenarios of pulsars also tend to endow them with different physical characteristics that were described above. In particular, Type II pulsars tend to have had stronger initial magnetic fields, another criterion that can be used to differentiate the two types. Since the criteria mentioned above require a value for the spin-down rates, $\dot{P}$, only 361 of the 422 pulsars in this study can be categorized as being either Type I or Type II.

2.3 *Ages*

Early estimates of pulsar ages use a simple model that assumes a constant effective magnetic dipole moment and that the present period is longer than the initial period. Such a characteristic age, τ_c, is given by

$$\tau_c = \frac{1}{n-1}\frac{P}{\dot{P}} , \tag{2}$$

where n = braking index (usually $n = 3$) and P and $\dot{P}$ are the period and period derivative, respectively. Ages of pulsars derived from their kinematic properties tend to show that τ_c is an overestimate, especially if it is less than 10^7 years (Lyne, Anderson, and Salter 1982; Amnuel *et al.* 1986). The large values of τ_c are thought to be due to the decay in the magnetic dipole moment of the pulsar and the subsequent decrease of $\dot{P}$ with time (Lyne, Ritchings, and Smith 1975; Gerasimov, Nesphor, and Stepanyan 1984).

An alternative estimate of the pulsar ages is given by Gunn and Ostriker (1970) and Lyne *et al.* (1975). In this case the magnetic field decays exponentially with time and the age depends on the magnetic dipole decay time scale, τ_d. The following relation defines the age,

$$\tau = \frac{1}{2}\tau_d \ln\left(1 + \frac{2\tau_c}{\tau_d}\right) , \tag{3}$$

where τ is the age and τ_c is defined by equation (2). The value of τ_d is estimated to be between 10^6 and 5×10^8 years with τ_d generally taken to be 9.1×10^6 years (Lyne *et al.* 1985). Though the ages derived by equation (3) may not be wholly accurate due to the uncertainty of the initial period of pulsars (Narayan 1987), they are consistent and provide the best estimate for ages.

Following the procedure outlined by Huang *et al.* (1985), pulsars can be divided into two groups. It is found that of the 361 pulsars 247 are Type II and 114 are Type I. Those that are Type II have ages given by equation (3). Type I pulsars have ages derived by the relation given by Huang (1987). The distribution of ages for both types of pulsars is shown in Figures 3a and 3b. The limit for Type II's is approximately $\log(\tau) = 7.4$ while Type I's have ages extending beyond $\log(\tau) = 8.0$, regardless of the method by which their ages are derived. Generally, Type II pulsars will not have had the time for them to move far from their place of origin; thus, they are better suited for use as spiral arm tracers. Also, their Population I origins point to them as being more appropriate indicators of spiral structure.

2.4 *Velocities*

Proper-motion surveys of pulsars have yielded mainly high space velocities. The high velocities are thought to be due to either the disruption of a close binary system or from an asymmetric supernova explosion (Gunn and Ostriker 1970). In the survey of Lyne *et al.* (1982) the rms space velocity is 210 km s^{-1}, with both high (~ 400 km s^{-1}) and low velocities observed. Tutukov, Chugai, and Yungel'son (1984) have analyzed these data and find that for nearby pulsars ($d \leq 500$ pc) the rms space velocity is less than 50 km s^{-1}. This would indicate that there is a bias for high-velocity pulsars to also be distant. Huang, Deng, and Xia (1987) find for Type I pulsars an average space velocity of 40–50 km s^{-1}, while Type II's have velocities of about 160 km s^{-1}. Even with large velocities there is a tendency for Type II pulsars to have ages less than 10^7 years, and the furthest such a pulsar could travel would be ~ 1.5 kpc. This would not have a noticeable effect on the present problem since such a high-velocity pulsar would have to be directed nearly perpendicularly away from the spiral arm to become completely disassociated with its place of origin.

2.5 *Spiral Pattern*

The position of pulsars when they were born can be determined from their ages, velocities around the galactic center, and present positions. The galactic orbital velocities of disk objects like supernovae remnants and H II regions allows one to assign a similar velocity to other Population I objects, i.e., Type II pulsars. A rotation curve for disk stars taken from Shuter and Gill (1985) is combined with the individual galactocentric distances to determine the rotational velocities for the Type II pulsars. These velocities and the ages are used to estimate the distance that the individual pulsars have traveled in their lifetimes in an orbit about the Galaxy. For most pulsars the distance is not great due to the low value of τ compared to the galactic orbital periods.

The birth positions of Type II pulsars can be combined to form spiral arm patterns by taking into account the pattern velocity. The pattern velocity is assumed to be uniform and follows the relation $\Omega_p = 13.5$ km s^{-1} kpc^{-1}. By applying this relation to the individual pulsars it is possible to determine the position of the spiral pattern at

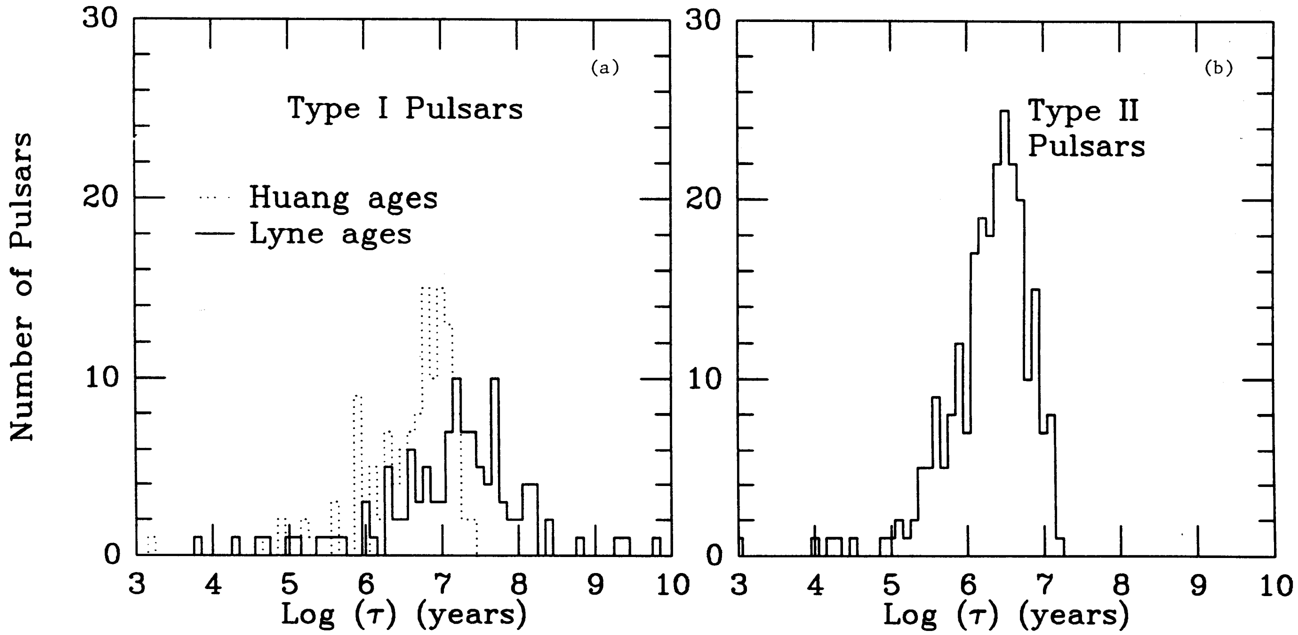

FIG. 3–The age distribution of the pulsars for the different types. (a) The ages for Type I pulsars are determined using both equation (3) from Lyne *et al.* (1975) and the relation given by Huang (1987). (b) Ages for Type II pulsars are found using equation (3).

any time in the past and to combine the pulsars of different ages into a spiral pattern. This was done without assuming the number of spiral arms or the pitch angle, i, which is defined as the angle between a unit vector in the cylindrical coordinate θ direction and the tangent to the spiral arm. The resulting positions of the Type II pulsars are shown in Figure 4 in a $\log R,\theta$ diagram. The large concentration of pulsars at the position of the Sun, ($\log R_\odot = 3.93$, $\theta_\odot = 360°$), is to be expected due to selection effects.

There are indications for arm segments as shown in Figure 4 by the lines of logarithmic spiral patterns which appear as straight lines on a $\log R,\theta$ plot. The best fit to the data is a spiral arm segment with a pitch angle of 14°.5. This is also the best fit for pulsars in their present location, as can be seen in Figure 1. One of the important differences between Figures 1 and 4 is the effect of individual pulsar orbital motions around the Galaxy and the motion of the spiral pattern. These motions are accounted for in Figure 4, while in Figure 1 selection effects cause most pulsars to be located at 360°, i.e., near the Sun. Also, the use of only Type II pulsars in Figure 4 is an important difference. A similar plot of only Type I pulsars would produce no discernible patterns. Since Figures 1 and 4 are similar, the need to distinguish between pulsar types does not appear to be essential in order to find spiral patterns, though it does reduce the scatter in such plots.

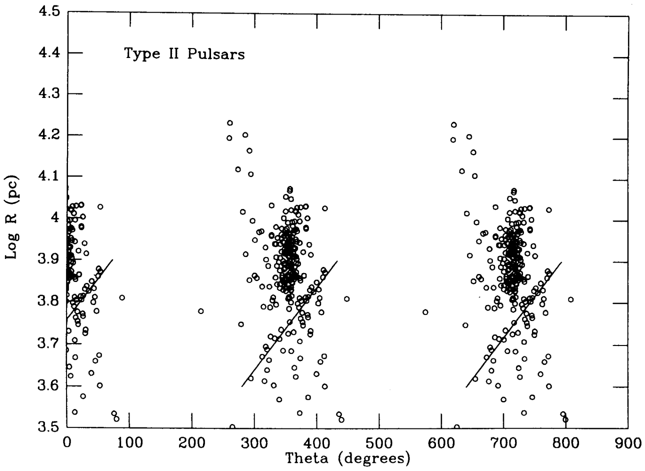

FIG. 4–The positions for Type II pulsars in a $\log R,\theta$ diagram. The motions of the pulsars around the galactic center and the spiral pattern motion have been taken into account. The lines represent a logarithmic spiral arm segment with a pitch angle, $i = 14°.5$.

3. Discussion

Type II pulsars are extreme Population I objects and it is expected that they should show indications of the regions of their origin. Figures 1 and 4 indicate that Type II pulsars can be used as indicators of spiral arm structure and can trace the evolution of the spiral pattern.

By comparing Figures 1 and 4 to those of Elmegreen (1985), it is clear that there are some differences. The surveys of spiral arm tracers mentioned by Elmegreen include a large number in the outer part of the Galaxy, while the pulsar surveys do not adequately cover this region. The spiral patterns discussed by Elmegreen range from two to four arms with pitch angles from 6 to 27 degrees. The segment that is shown in Figure 4 would correspond to the Sagittarius-Carina arm shown by Elmegreen. It should be remembered that the $\log R,\theta$ diagrams shown by Elmegreen have $\log R_\odot = 4.0$ and $\theta_\odot = 180°$. As is mentioned by Elmegreen, the number of spiral arms is very uncertain and debatable. It is possible to fit two, three, or four arm segments to the $\log R,\theta$ plot of Elmegreen.

4. Conclusions

The use of pulsars as a tracer of the spiral arm pattern of the Galaxy has been examined with successful results. There is an indication of a spiral arm segment using the following assumptions.

(a) The electron density of the Galaxy follows the relation given in equation (1).

(b) Pulsars can be distinguished by their present characteristics into two types.

(c) The ages of Type II pulsars can be determined using equation (3), which accounts for the change in spin-down rate due to the decaying magnetic dipole moment.

(d) The spiral pattern motion is uniform and its shape has not altered significantly during the last 10^7 years.

The data for pulsars are very strongly influenced by selection effects, as can be seen in Figures 1 and 4. The best fit to the data indicates a local spiral arm segment pattern with a pitch angle of 14°.5. Because of the limited range of the data it is not possible to determine what the galactic pattern would be, if there actually is one. A larger number of pulsars from deep surveys are needed to continue and expand the results found here. In particular, surveys beyond the solar neighborhood are needed to map out the spiral arm structure. There is a concentration of pulsars within the solar circle, mainly at galactocentric distances of 7 to 9 kpc, which can be seen in Figure 1. On the other hand, the number of pulsars beyond the solar circle is very small. There should be an emphasis on surveys in the outer part of the Galaxy to provide indicators of spiral structure. Pulsar locations, periods, period derivatives, and dispersion measures are required.

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