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Do pulsars define a spiral pattern?

A.A. Deshpande

Raman Research Institute, Bangalore 560 080

Abstract. In this paper, we address the question "Do pulsars define a spiral pattern?". Based on a detailed statistical analysis, we show that there exists a significant correlation between the present distribution of pulsars and the mass distribution (in the spiral arms) expected to exist about 60 Myr ago (Ramachandran & Deshpande 1994). We discuss one of the most important implications of this correlation and estimate the lower critical mass for the formation of the neutron star to be about $7M_{\odot}$. We compare this estimate of the lower critical mass with an estimate obtained from other methods.

Key words: Pulsar: distribution—galaxy: structure—stars: end states

1. Introduction

We would like to address here an important question "Do pulsars define a spiral pattern?". In other words, we can ask whether the spatial distribution of pulsars in our Galaxy has any correlation with the spiral arm structure of the Galaxy.

Ever since their discovery, pulsars have been the subject of many statistical studies. However, the importance of the connection between the birth places of pulsars and the locations of the spiral arms was not emphasized until the work of Blaauw in 1985. From a detailed consideration, Blaauw (1985) argued that the 'local' birthrate of pulsars should equal the 'local' deathrate of massive stars. The 'local' region, he was considering, is that within half a kiloparsec from the Sun.

After examining the death - rate of stars in the nearby OB associations, he arrived at a rather surprising conclusion. He found that the local population of pulsars cannot be replenished by the massive O-B stars alone which are usually found in the associations. Lower mass field stars, that is, those not belonging to associations, must therefore make an important contribution.

It turns out that given the estimates of pulsar birthrate, the progenitors of the overwhelming majority of local pulsar population must be relatively old field stars in the mass range 6-10 $M_\odot$. If this conclusion is correct then as Blaauw put it, "Pulsars are, on a galactic scale, tracers of regions of past spiral structure rather than of active spiral structure." Let us explain this. If the progenitors of the majority of pulsars were massive stars, then one would expect the majority of pulsars also to be located close to the leading edge of the spiral arms. But if the majority of the pulsars have progenitors less massive than, say, 10 $M_\odot$, since the lifetime of their progenitors are rather long, one would expect these stars to explode at significant distances from the leading edge of the spiral arms. Consequently, the location of the majority of pulsars should not have any strong correlation with the present locations of spiral arms. This is because, there is a relative motion between the spiral density waves which are 'delineated' by the spiral arms, and the matter in the Galaxy.

Does the matter distribution lead the spiral pattern, or lag behind it? Since the Galaxy is differentially rotating and the spiral pattern is rigidly rotating, inside a critical radius which one may call the corotation radius, spiral pattern will be lagging behind the matter, and outside this radius the matter will lag behind the spiral pattern. Extensive extragalactic observations, as well as detailed dynamical modelling of the gas distribution and their motions in our Galaxy seem to suggest that this corotation radius is approximately 12-15 kpc, that is well outside the solar circle. In other words, as far as the majority of pulsars are concerned, their circular velocities should be larger than that of the spiral pattern at the corresponding radius, and therefore they should be ahead of the spiral patterns.

2. Correlation between the present pulsar distribution and the mass distribution (in the spiral arms) at past epochs

About an year ago, we set out to test (Ramachandran & Deshpande 1994) this remarkable conjecture by Blaauw. What we did was the following. We tried to look for a correlation between the present distribution of the pulsar population and the location of the spiral arms in the past. An essential ingredient into this analysis is the distance estimates to the observed population of pulsars. We have used the recent comprehensive model of the electron density distribution in the Galaxy derived by Taylor and Cordes (1993). This model and the dispersion measures of pulsars, which give the column density of electrons along the sight-lines, are used to estimate the distances to pulsars. The distribution of pulsars derived from this model projected on to the plane of the Galaxy is shown in Fig. 1. Here, the 'dots' indicate the known pulsars, and the 'contours' describe the electron density distribution due to Taylor and Cordes. As may be seen from this distribution, the observed density of pulsars is systematically higher in the solar neighbourhood as might be expected from various selection effects. To be able to properly quantify and correct for such a bias, we restricted our sample to those pulsars which, in principle, should have been detected by any one of the eight major pulsar surveys.

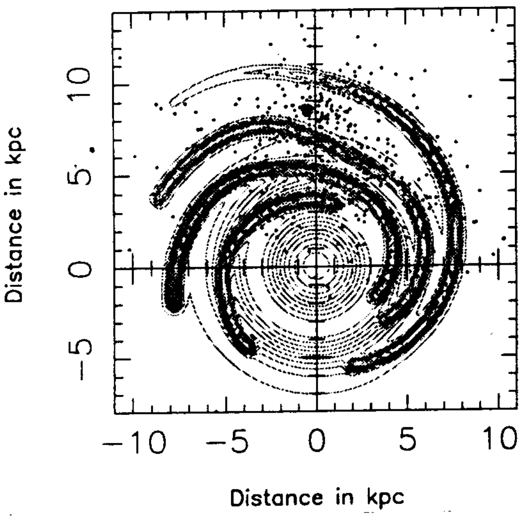

Figure 1. The new electron density distribution model of Taylor & Cordes (1993). Projected locations of all known pulsars are plotted as dots. Sun is at (0, 8.5) . (Fig. taken from Ramachandran & Deshpande 1994.)

The next step is to construct the galactic distribution of the *true* population of pulsars from the *observed* population. This involves computation of the so called scale factors which are measures of the undersampling of the *true* population. While discussing pulsar current or birthrates, one is interested in calculating a scale factor as a function of the rotational parameters of the pulsars - a quantity which is averaged over some assumed spatial distribution of pulsars in the Galaxy. In the present context, one wants to ask a slightly different question. Given the location in the Galaxy where a pulsar has, in fact, been discovered, one wants to know what is the probability of its detection. This will enable us to calculate the scale factors as a function of the position in the Galaxy. This was done by using the 'true' distribution of pulsars in the magnetic field-period (B-P) plane as derived by Deshpande, Ramachandran, & Srinivasan (1994). They derive this distribution from the observed number by accounting for selection effects estimated as a function of pulsar period and magnetic field. The 'true' distribution in the B-P plane, in other words, is equivalent to a probability distribution of the periods and magnetic fields. Therefore, given a particular location in the Galaxy, and given this probability distribution for the occurrence of periods and magnetic fields, one can calculate the detection probability or the fraction of pulsars at that location that are likely to be discovered in any of the eight surveys.

To summarize the above discussion, we calculate the scale factors as a function of the galactocentric radius R and the azimuth, by using this 'true' B-P distribution of pulsars. As mentioned earlier, there is a relative (azimuthal) angular motion between the spiral pattern and the matter in the Galaxy. Assuming a flat rotation curve for the Galaxy one can rotate the pulsar distribution, as it were relative to the spiral arms to look for a correlation between the two at some past epoch. The expected correlation can, in principle, be smeared by three effects: first, by the spread in the birth places of the progenitors themselves; second, by the motion of the progenitors between their birth and death; and third, by the motion of the pulsars themselves after their birth. The first two effects are expected to be relatively unimportant, but the effect of pulsar motion need not be. In spite of this if one does find a correlation then one can turn it around to estimate the motion of the pulsars themselves.

Before giving the result of our analysis, let us state two assumptions that have explicitly gone in. The first one is that the "arm component" of the electron density in the model of Taylor and Cordes (1993) adequately describes the mass distribution in the spiral structure itself. We consider this assumption as reasonable since this electron density model is based on the observations of giant HII regions. Second, in order to define the circular velocity of the spiral pattern we have assumed a value of 14 kpc for the corotation radius. As mentioned earlier, this value is consistent with detailed modelling of the Galaxy with HI data.

Our conclusions regarding the correlation between the present pulsar distribution and the location of the spiral arms at past epochs in shown in Fig. 2. Surprisingly, there are two significant features: one corresponding to about 60 Myr ago, and the other to the present epoch. In our opinion, the latter correlation, namely at the present epoch is most likely an artefact of the apparent clustering of pulsars in the arm regions. This can happen, for example, if the arm density in the electron distribution is over-estimated relative to the smooth component. This can also happen if the location of the spiral arms derived from the model is in error with respect to their true positions. If the correlation feature at the present epoch is due to artificial clustering of pulsars in the arm, then one would expect it to be more pronounced in the inner Galaxy. This is, indeed, the case. The specific pulsars which contribute to this feature are mainly between 4 to 7 kpc from the galactic centre.

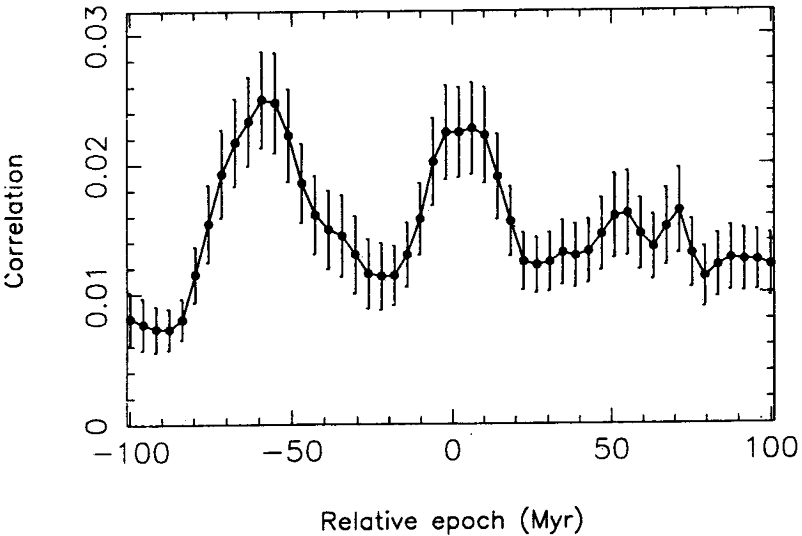

Figure 2. Plot of the correlation of the mass distribution in the spiral pattern at various epochs with the present pulsar distribution. This plot corresponds to a corotation radius of 14 kpc. The error bars indicate 1σ deviation on either side. (Fig. taken from Ramachandran & Deshpande 1994)

Considering this, it is tempting to suggest that one should in fact use the reduction in the strength of this feature at the present epoch as a necessary criterion to assess and aid further refinements of the electron density model. Hereafter, I will not discuss this feature and instead will turn my attention to the correlation between the distribution of pulsars and the location of spiral arms some 60 Myr ago.

The question one has to ask at this stage is whether this feature is real or whether this, too, is an artefact. In order to test the statistical significance of this feature, we did the following test: we scrambled the longitudes of the pulsars and repeated the whole analysis. From the distribution of the maximum correlation obtained from about 40,000 trials we concluded that the correlation maximum at –60 Myr has a significance level of 99.95%. We also randomly varied the derived distances to pulsars by about 30%. This test showed even higher significance. A similar exercise showed that the correlation maximum at the present epoch has a much smaller significance, of about 93%.

To summarize this part of the discussion, our detailed analysis of the galactic distribution of pulsars confirms the prescient conjecture by Blaauw that "Pulsars on a galactic scale are tracers of regions of past spiral structure rather than the active spiral structure".

3. Lower critical mass for the formation of neutron stars

One of the most important implications of this correlation and the relative epoch at which it peaks is to be understood in terms of the minimum mass for the neutron star formation. Let us see how it is so. As we have seen, the correlation peaks at –60 Myr. This means that the epoch of formation of stars which gave birth to most of the present population of pulsars was about 60 Myr ago. To a first approximation, this timescale is the sum of the lifetime of the progenitors of pulsars and the average age of the present population of pulsars. We can estimate the average age of pulsars in the present sample as follows. We can use the characteristic ages of the pulsars in our sample as reasonable estimates of their ages, the characteristic age being defined as the ratio of the period and two times the first derivative of the period. A weighted average for the sample, then, can be computed by using the scale factor weightage as similar weighting was used in computing the correlation.

This average age turns out to be 10±2 Myr. Therefore, the average lifetime of the progenitors is about 50 Myr. It is worth mentioning here that when we selected pulsars in different average age ranges, the correlation peak corresponding to the past epoch was seen to shift systematically implying a roughly constant value for the lifetime of the progenitor stars. Now the lifetime of about 50 Myr would correspond to a 7 $M_\odot$ star. Since the initial mass function of stars is believed to be very steep, that is, the number of stars increase very rapidly as one goes to lower masses, it is reasonable to assume that the majority of pulsars come from progenitors with masses just above the cut-off mass for the formation of neutron stars. As we do not expect any particular correlation of the lifetime of pulsars with the mass of the progenitor, the above assumption should hold good.

Reduced correlations are expected from pulsars formed from more massive progenitors which should show up at more recent epochs consistent with the evolution timescales of the progenitors. A significant tail corresponding to such more recent epochs is clearly seen in this figure. Therefore we would like to conclude that about $7M_{\odot}$ is the lower critical mass for the formation of the neutron stars.

While associating the inferred evolution timescale of about 50 Myr with a mass of the progenitor of about 7 $M_{\odot}$, we make an implicit assumption that the progenitors are 'single' stars. If the progenitors with the above evolution timescale were to be in binaries, then the progenitors need to be more massive. This is because we expect the time interval between the star formation and the release of an 'observable' pulsar to be longer by as much as a factor of two or more, depending on the mass ratio, compared to the evolution timescale of the progenitors if they were single stars. Conversely, the single star fraction of the progenitors of a given mass will contribute collectively to the correlation over a narrow range of epochs, typically over the average age of pulsars. Whereas the remainder will contribute to the correlation at epochs spread over a wider range depending on the mass of the companion. Hence, the fact that the correlation seems to be peaking over a narrow range of epochs, should necessarily be interpreted as due to the contribution from 'single' progenitors. To summarize, the peak in the correlation at 60 Myr ago implies that the average lifetime of the pulsar progenitors is about 50 Myr. This corresponds to a star of about 7 $M_{\odot}$. So an interesting corollary of our analysis is that all stars above 7 $M_{\odot}$ should produce neutron stars.

It is important to compare this estimate of the lower critical mass for neutron star formation with other similar estimates. One of the other ways of determining this lower critical mass is an estimation of the birth rate of pulsars. Without going into the details of how the pulsar birth rates are computed, I would merely like to state some results. Based on the analysis of pulsar current, Deshpande, Ramachandran, and Srinivasan (1994) have estimated the birthrate of pulsars to be 1 in about 80 years. A few years ago, Narayan and Ostriker (1990) derived the birthrate of 1 in 100 years, and Lorimer and his colleagues (1993) estimate it to be 1 in 125 to 250 years. The pulsar birthrates compare reasonably well with some related rates such as the frequency of supernova explosions in our Galaxy and the birthrate of supernova remnants, given the uncertainties in estimating these rates.

If one takes this pulsar birth rate of 1 in 80 years literally, then what is the mass above which all stars must end their lives as neutron stars?. This boils down to comparing the death rate of stars with the birth rate of pulsars. If the star is sufficiently massive, then the birth rate can be assumed to be safely equal to the death rate. The birth rate of stars can be inferred from star counts and their theoretical lifetimes on the main sequence. This has been done by a number of people, however the birth rate and the death rate of stars have also considerable uncertainties in them. There is a further complication. The birth rate of stars derived from observations is a local birth rate since one can study stars within only a kpc or so of the Sun. The pulsar birth rate that we have is the Galactic rate. Therefore one has to convert the galactic birth rate of pulsars to a local birth rate (namely, number/pc square/yr) before the comparison can be made. In order to do this one has to assume an effective radius for the Galaxy to allow for a non-uniform radial distribution of massive stars, HII region, molecular clouds etc. When we convert the Galactic birthrate of pulsars (of 1 in 80 years) to a local rate by assuming an effective radius of 20 kpc and compare it with the integrated death-rate of stars obtained using the initial mass function due to Scalo (1986), we find that all stars above 15 $M_\odot$ should produce neutron stars. I would like to emphasize that the lower critical mass for the formation of neutron stars so derived is very sensitive to the assumed value of the effective radius of the Galaxy.

4. Summary

So, to conclude, let us repeat the main points: We find a significant correlation between the present spatial distribution of pulsars and the spiral structure about 60 Myr ago, i.e. pulsars do define the past spiral structure in spite of their motions during their lifetimes.

This correlation at 60 Myr ago implies a lower critical mass of single stars for the formation of neutron stars to be about 7 $M_\odot$. As pulsar statistic improves, one hopes to refine these estimates.

Acknowledgement

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