Astron. Astrophys. 242, 128–132 (1991)

ASTRONOMY AND ASTROPHYSICS

Radio pulsars and the scale height of ionized hydrogen

D. Bhattacharya [1,2,*] **and F. Verbunt** [3]

[1] Centre for High-Energy Astrophysics, NIKHEF-H, Kruislaan 409, NL-1098 SJ Amsterdam, The Netherlands
[2] Astronomical Institute "Anton Pannekoek", Roetersstraat 15, NL-1018 WB Amsterdam, The Netherlands
[3] Astronomical Institute, P.O. Box 80.000, NL-3508 TA Utrecht, The Netherlands

Received April 30, accepted August 21, 1990

Abstract. Some recently advanced models for the decay of the magnetic fields of neutron stars imply that functioning radio pulsars should be present at distances z in excess of 1 kpc from the galactic plane, contrary to the apparent z-distribution of known pulsars. We argue that the present upper bound of the apparent z-distribution may well be an artifact of the use of the dispersion measures to determine distances to pulsars. Dispersion measures of pulsars in globular clusters imply that the ionized gas responsible for the dispersion of pulsar signals has a scale height ~ 500–1000 pc. This would lead to an underestimation of the distances of pulsars far away from the galactic plane. Pulsars currently thought to be located at $z \lesssim 1$ kpc may in fact be at higher z.

Key words: interstellar medium: general – pulsars : general – stars: neutron – star: magnetic field – clusters: globular – Galaxy (the): disk of

1. Introduction

The idea that the magnetic fields of neutron stars decay in the timescale of $\lesssim 10^7$ yr has recently become the subject of a renewed debate (for a review see e.g. Bhattacharya 1989). With the discovery of several old radio pulsars with field strengths ranging from 10^8 to 10^{10} G it has become apparent that the decay of the magnetic fields stop at a certain "residual" value, and that the strength of this "residual" field varies between pulsars (see e.g. Kulkarni 1990). Detailed studies of the evolutionary scenarios for the X-ray pulsars Her X-1 and 4U1626-67 suggest that these neutron stars are $\gtrsim 10^8$ yr old, but have still retained magnetic fields $\sim 10^{12}$ G (Verbunt et al. 1990). The discovery of cyclotron lines in the spectra of a few gamma-ray bursters also indicate that some old neutron stars may have residual fields $\sim 10^{12}$ G (Murakami et al. 1988).

In order to accommodate these observational facts new theoretical models for the evolution of the magnetic fields have been proposed, which link the behaviour of the magnetic field explicitly with the evolution of neutron stars in binary systems (Shibazaki et al. 1989; Srinivasan et al. 1990; see also Bailes 1989; Taam & van den Heuvel 1986). According to these models little or no decay of the magnetic fields of isolated radio pulsars is expected till their rotation has slowed to the so-called "death line", at which point pulsar activity stops. Depending on the strength of the magnetic field the pulsar may take upto several times 10^7 yr to reach the death line by spinning down. Since radio pulsars have velocities of order 100 km s^{-1} in the z-direction (Lyne et al. 1982; Cordes 1986), a good fraction of these pulsars are expected to move to a distance $z > 1$ kpc from the galactic plane despite being born very close to it. However, with the exception of some radio pulsars in globular clusters, no radio pulsars are known with z significantly in excess of 1 kpc.

In this paper we argue that pulsars at high z may indeed exist, perhaps even among the known ones, and that the upper limit to the apparent z-distribution of radio pulsars could very well be the consequence of the finite scale height of ionized gas in the galaxy, combined with the fact that the inferred distances of pulsars are based on their dispersion measures. In Sect. 2 we discuss how the discovery of radio pulsars in globular clusters has provided a measure of the vertical extent of the ionized gas. The effect of this on the apparent z-distribution of radio pulsars is described in Sect. 3, and other implications are explored in Sect. 4.

2. Radio pulsars in globular clusters as a probe of the ionized gas

As pointed out by Reynolds (1989), the radio pulsars in globular clusters offer a unique possibility to study the vertical scale of the ionized hydrogen distribution in our galaxy. For an electron density distribution of the form

$$n_e(z) = n_e(0)\, \mathrm{e}^{-z/h} \tag{1}$$

the dispersion measure DM, defined as the integrated electron density along the line of sight to a radio pulsar at a distance d and with a galactic latitude b would be given by

$$DM \sin|b| = n_e(0)\, h\,(1 - \mathrm{e}^{-z/h}), \tag{2}$$

where $z = d \sin|b|$ is the distance of the pulsar from the galactic plane. The distances to most radio pulsars in the galactic disk are obtained from their dispersion measures, by assuming an electron density distribution consisting of two distinct components. The first one, with $n_{e,1}(0) \simeq 0.015\,\mathrm{cm}^{-3}$ in the solar neighbourhood, corresponds to the H II regions around massive stars, and is confined to small distances from the galactic plane, with a scale

Send offprint requests to: D. Bhattacharya (at Astronomical Institute "Anton Pannekoek")

* On leave from Raman Research Institute, Bangalore, India

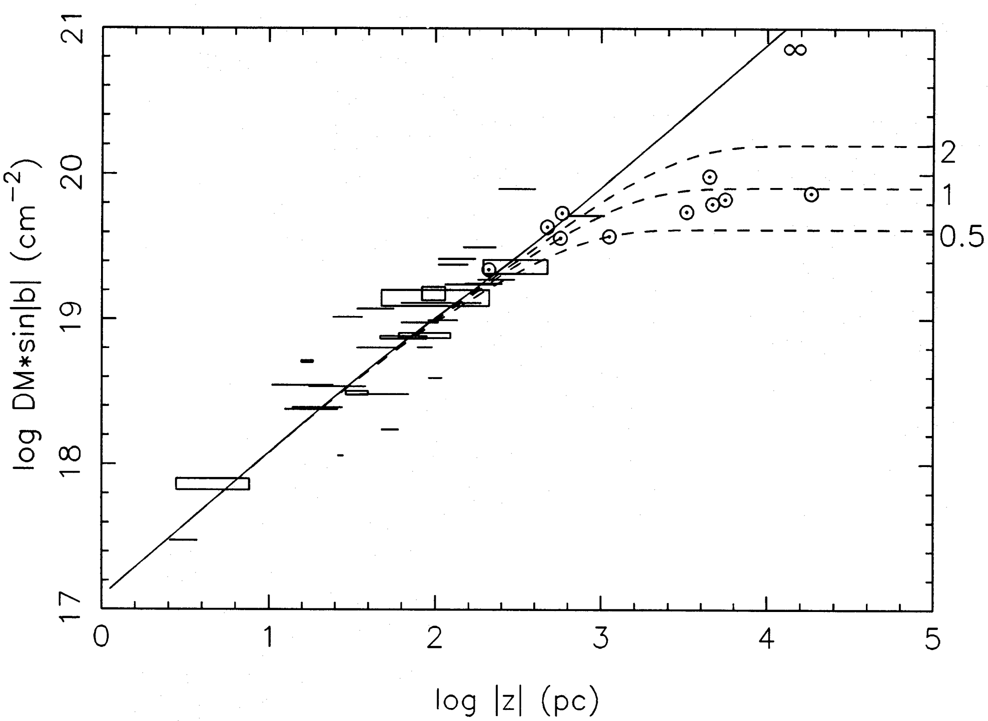

Fig. 1. The dispersion measure *DM* measured in the direction perpendicular to the galactic plane as a function of distance $|z|$ to the galactic plane. The lines are those for a two-component model of the galactic electron density, with an extended component with a scale height of 0.5, 1, 2 kpc, or of infinite height. The radio pulsars for which distances are known are shown as boxes or lines, whose extent corresponds to the observational uncertainties. The globular cluster pulsars are indicated as ⊙. The small *DM* of the cluster pulsars indicates that the scale height of the extended component of the electron density is $\lesssim 1$ kpc (After Reynolds 1989)

height $h_1 \simeq 70$ pc. The second component with $n_{e,2}(0) \simeq 0.025$ cm^{-3} in the solar neighbourhood, has so far been assumed to have an infinite scale height.

In Fig. 1, adapted after Reynolds (1989), we show the dispersion measure according to this two-component model for n_e, for scale heights $h_2 = 0.5$, 1.0, 2.0 kpc and $h_2 = \infty$ for the second component. The figure also shows the dispersion measures of the radio pulsars in the galactic disk with independent distance measurements, as listed by Reynolds (1989). These dispersion measures are seen to be consistent with all the four model curves.

Radio pulsars in globular clusters, on the other hand, have sufficiently large distances from the galactic plane to allow a determination of the scale height of the second component of the electron density. Reynolds (1989) used the dispersion measures of radio pulsars in four globular clusters to infer a scale height $h_2 \sim 1.5$ kpc for this component. With the discovery of many more radio pulsars in globular clusters since then (Table 1) it is now possible to set even better limits. As can be seen from Fig. 1, the present estimate of the scale height h_2 lies in the range 500–1000 pc (see also Manchester et al. 1990).

3. Consequences for the *z*-distribution of radio pulsars

A consequence of the finite scale height of the electron density in our galaxy is that the dispersion measure of a radio pulsar does not increase once the pulsar has a distance to the plane in excess of about 1 kpc. In other words, if one uses a model with infinite scale height for the extended component of the electron density ($h_2 = \infty$), *all pulsars with* $z > 1$ kpc *will be derived to have* $z \lesssim 1$ kpc. More specifically, if the dispersion measures of pulsars in NGC 6624 and M 15 are representative of the range of maximum dispersion measure in the *z*-direction, pulsars at $z \gtrsim 1$ kpc will have derived distances between ~ 500 pc and 1 kpc. This is readily appreciated from an inspection of Fig. 1.

In our opinion, there are indications that some of the known pulsars indeed have much higher distances to the galactic plane than hitherto assumed. In Fig. 2a we show the number of known pulsars as a function of distance *d*, selecting only older pulsars, with characteristic ages $\tau_c \equiv P/(2\dot{P}) > 2\ 10^7$ yr (we exclude from the present discussion the pulsars discovered in the recent Jodrell Bank survey (Clifton & Lyne 1986), because this survey was conducted specifically at low galactic latitudes, and was therefore unsuitable for pulsars at large distances from the galactic plane). Although the number of such pulsars drops rapidly with distance due to luminosity selection effects, more than a third of the known pulsars is more than 2 kpc removed from us.

In Fig. 2b we show the number of known pulsars as a function of distance *z* from the galactic plane (derived assuming $h_2 = \infty$), again selecting those with $\tau_c > 2\ 10^7$ yr. The *z*-distribution does not extend beyond about 1 kpc. (Notice that the scale for Fig. 2b has been expanded with respect to that of Fig. 2a). Velocity measurements of radio pulsars (Lyne, Anderson and Salter 1982; Cordes 1986) show that the *z*-component of the velocity of a radio pulsar is on average $v_z \sim 100$ km s^{-1}. At such velocities, many pulsars should reach $z > 1$ kpc at ages $> 10^7$ yr. This is illustrated in Fig. 3, which shows the distance from the galactic plane reached by a pulsar, as a function of time, and as a function of its initial velocity in the *z*-direction. Pulsars starting out with magnetic fields $\lesssim 6\ 10^{12}$ G will continue to function beyond this age (albeit with a decreasing luminosity) if little or no decay of the magnetic field occurs, and one would expect to find a fair fraction (decided by the v_z-distribution) of them at distances significantly exceeding 1 kpc from the galactic plane.

We think that the absence of known pulsars at these heights is an artifact of the assumed infinite scale height of the extended component of the electron density.

If our line of reasoning is correct, one expects to see an enhancement of the number of radio pulsars at 500 pc $\lesssim |z| \lesssim 1$ kpc. Figure 2b does seem to show such an enhancement, especially at positive z. However, an interpretation of Fig. 2b along these lines is complicated by the asymmetry between the distributions at positive and negative z. There may be a number of factors responsible for this asymmetry. It has been suggested that there is a layer of excess electron density at small negative distance to the galactic plane, or, alternatively, that the sun is slightly above the plane of symmetry of an otherwise symmetric distribution (Harding & Harding 1982). Also the surveys in which many of the known pulsars were discovered do not cover both sides of the galactic plane with similar sensitivity. Until this asymmetry is better understood, the presence or absence of an excess in the number of pulsars at derived distances to the galactic plane $500\,\mathrm{pc} < |z| < 1\,\mathrm{kpc}$ cannot be settled. A more detailed investigation of this question is now in progress. Nevertheless, if the idea of magnetic field decay being related to the processing of neutron stars in binaries is correct, then one predicts that a deep survey at high galactic latitudes should provide evidence for an enhanced number of pulsars at derived distances from the galactic plane around 750 pc.

4. Discussion

The finite scale height of the ionized hydrogen distribution implies that we cannot exclude the presence of functioning radio pulsars with strong magnetic fields at $|z| \gtrsim 1\,\mathrm{kpc}$.

The suggestion that radio pulsars with strong fields may exist at high $|z|$ does help to remove the anomaly of Her X-1, first noted by Lamb (1981). The fact that this X-ray binary has a distance of ~ 3 kpc from the galactic plane sets this neutron star apart from all other known neutron stars with strong fields, if the derived $|z|$-values for the latter were correct (see Fig. 2). Extension of the radio pulsar distribution to higher $|z|$ helps remove this anomaly.

The gravitational field of the galactic disk would decelerate a pulsar sufficiently for it to fall back towards the galactic plane after several times 10^7 yr. Most pulsars, however, would have spun down beyond the death line by this time; as a result, one does not expect to see a large number of radio pulsars with a velocity in the direction towards the galactic plane.

Table 1. Dispersion measures of pulsars in Globular clusters

PSR	l (deg)	b (deg)	Cluster	Distance (kpc)	DM ($\mathrm{cm^{-3}\,pc}$)	$\lvert z\rvert$ (kpc)	Ref.
0021−72A[a]	306	−45	47 Tuc	4.6	67	3.3	1, 2
0021−72B[a]	306	−45	47 Tuc	4.6	65	3.3	2
0021−72C	306	−45	47 Tuc	4.6	25	3.3	3
1310+18	333	+80	M 53	18.5	24	18.2	4
1516+02A	4	+47	M 5	7.6	29.5	5.6	5
1516+02B	4	+47	M 5	7.6	29.5	5.6	5
1620−26	351	+16	M 4	2.1	63	0.58	6
1639+36	59	+41	M 13	7.1	30.5	4.7	7
1745−24	4	+ 2	Ter 5	7.1	240	0.25	8
1746−20	8	+ 4	NGC 6440	7.1	210	0.5	9
1820−30A	3	− 8	NGC 6624	8.0	86	1.1	10
1820−30B	3	− 8	NGC 6624	8.0	86	1.1	10
1821−24	8	− 5	M 28	5.8	120	0.92	11
2127+11A	65	−27	M 15	9.7	67.3	4.4	12
2127+11B	55	−27	M 15	9.7	67.2	4.4	13
2127+11C	65	−27	M 15	9.7	67.2	4.4	14

[a] As the dispersion measure produced by galactic electrons in the line of sight to 47 Tuc we adopt that of PSR 0021−72C, i.e., the smallest of the three values.

References:
1. Ables J.G. et al., 1989, Nat 342, 158
2. Ables J.G. et al., 1988, IAU Circ. No. 4602
3. Manchester R.N., et al., 1989, IAU Circ. No. 4892
4. Anderson S. et al., 1989, IAU Circ. No. 4853
5. Wolszczan A., et al., 1989, IAU Circ. No. 4880
6. McKenna J. & Lyne A.G., 1988, Nat 336, 226
7. Anderson S. et al., 1989, IAU Circ. No. 4819
8. Lyne A.G. et al., 1990, IAU Circ. No. 4974
9. Manchester R.N. et al., 1989, IAU Circ. No. 4905
10. Biggs J.D. et al., 1990, IAU Circ. No. 4988
11. Foster R.S. et al., 1988, ApJ 326, L13
12. Wolszczan A. et al., 1989, Nat 337, 531
13. Anderson S. et al., 1989, IAU Circ. No. 4762
14. Anderson S. et al., 1989, IAU Circ. No. 4772

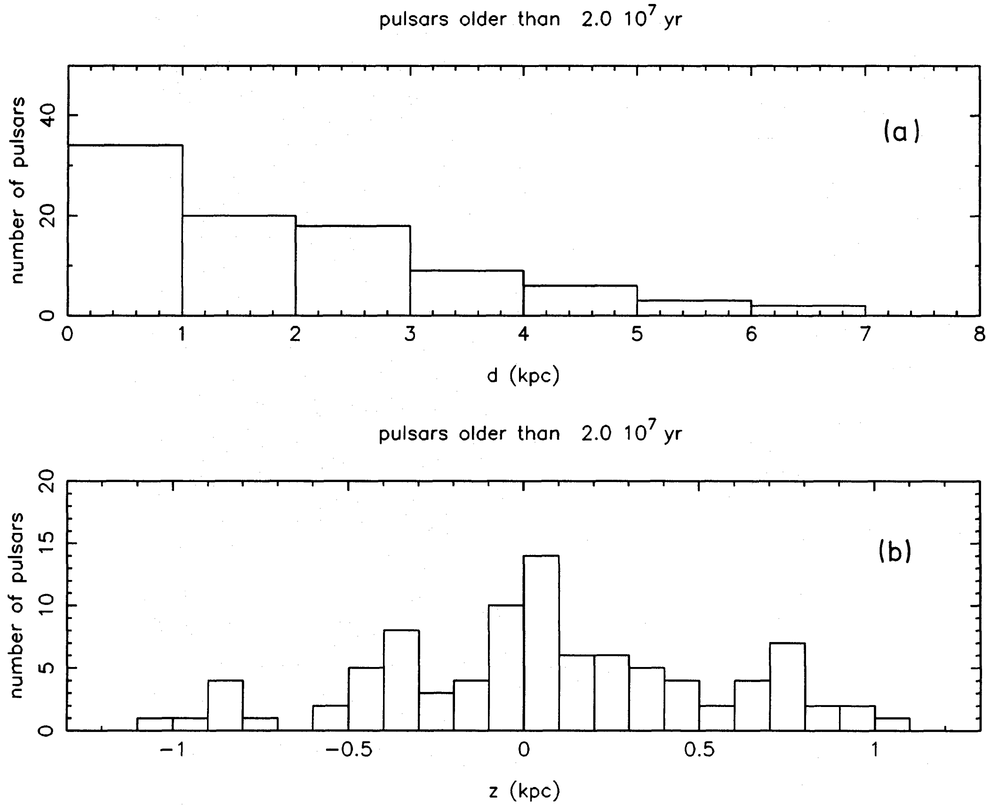

Fig. 2. **a** Histogram of the distances of pulsars with spindown ages larger than 2 10^7 yr. Millisecond pulsars, pulsars in binaries and the pulsars discovered in the recent Jodrell Bank survey (Clifton & Lyne 1986) have been excluded (see text). **b** The apparent z-distribution of the same pulsars

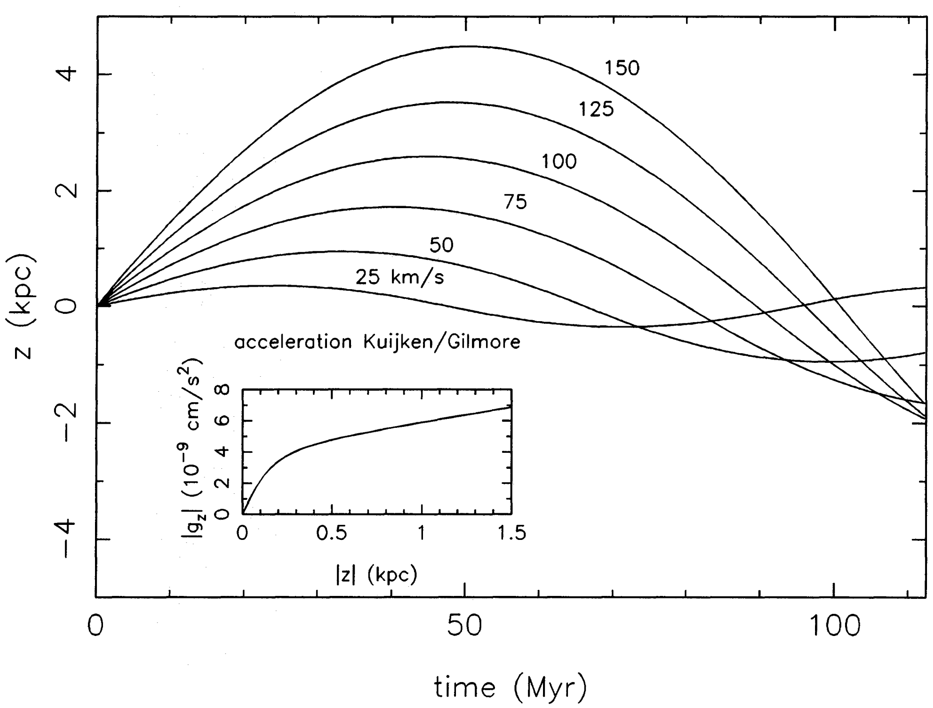

Fig. 3. Distances from the galactic plane reached by radio pulsars with different initial velocities in the z-direction as a function of age. The different curves are labelled with the appropriate initial v_z. The inset shows the model for the acceleration in the z-direction, adopted from the determination by Kuijken & Gilmore (1989)

If the γ-burst sources are neutron stars with relatively high magnetic fields, as indicated by the cyclotron absorption lines discovered in GB880205 (Murakami et al. 1988), a higher z-distribution of such neutron stars helps in explaining the isotropic distribution of such sources over the sky. As such γ-ray sources could be old enough to have passed the death-line, they could be moving either away from or towards the galactic plane.

In conclusion, we would like to urge extreme caution in the use of the apparent z-distribution of pulsars in studying statistical properties of the pulsar population, including the decay of their magnetic fields. Our view of the spatial distribution of pulsars is strongly dependent on the distribution of thermal electrons in the galaxy, which provides the basic distance scale. Statistical studies based on the z-distribution of pulsars are likely to be unreliable unless all the features of the electron distribution are well understood, and properly taken into account. For example, a finite scale height of the electron layer around 500–1000 pc, as indicated by pulsars in globular clusters, may very well be responsible for creating an apparent second population of pulsars situated at a large distance from the galactic plane, as found in a recent study (Narayan & Ostriker 1990), by artificially decreasing the derived distances of pulsars in the "tail" of a more extended z-distribution.

Acknowledgements. We thank R. D. Blandford and E. S. Phinney for discussions and comments on an earlier version of the manuscript.

References

Bailes M., 1989, ApJ 342, 917
Bhattacharya D., 1989, in: 23rd ESLAB Symposium, X-ray Astronomy, Vol. 1, X-ray binaries, eds. J. Hunt, B. Battrick, ESA SP-296, p. 179
Clifton T.R., Lyne A.G., 1986, Nat 320, 43
Cordes J.M., 1986, ApJ 311, 183
Harding D.S., Harding A.K., 1982, ApJ 257, 603
Kulkarni S.R., 1990, in: Neutron stars and their birth events, ed. W. Kundt, NATO ASI series, Kluwer, Dordrecht, p. 59
Kuijken K., Gilmore G., 1989, MNRAS 239, 605
Lamb F.K., 1981, in: IAU Symp. 95: Pulsars, eds. W. Sieber, R. Wielebinski, Reidel, Dordrecht, p. 309
Lyne A.G., Anderson B., Salter M.J., 1982, MNRAS 201, 503
Manchester R.N., Lyne A.G., D'Amico N., Johnston S., Lim J., Kniffen D.A., 1990, Nat 345, 598
Murakami T., Fujii M., Hayashida K., Itoh M., Nishimura J., Yamagami T., Conner J.P., Evans W.D., Fenimore E.E., Klebesadel R.W., Yoshida A., Kondo I., Kawai N., 1988, Nat. 335, 234
Narayan R., Ostriker J.P., 1990, ApJ 352, 222
Reynolds R.J., 1989, ApJ 339, L29
Shibazaki N., Murakami T., Shaham J., Nomoto K., 1989, Nat. 342, 656
Srinivasan G., Bhattacharya D., Muslimov A.G., Tsygan A.I., 1990, Current Science 59, 31
Taam R.E., van den Heuvel E.P.J., 1986, ApJ 305, 235
Verbunt F., Wijers R., Burm H., 1990, A & A 234, 195