THE RADIO LUMINOSITY OF PULSARS AND THE DISTRIBUTION OF INTERSTELLAR ELECTRON DENSITY

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Abstract. The radio luminosities of pulsars are given as functions of their period and the time variation of the period. The parameters of that dependence are calculated and independent distances are determined for pulsars. The average electron densities toward the pulsars are determined from the known dispersion measures. The results obtained are used to study the large-scale electron density distribution in the Galaxy. The distribution maximum lies in the vicinity of the Sagittarius spiral arm. The electron density falls off exponentially in the regions between spiral arms.

1. Introduction

The main observational characteristics have now been determined for most of the pulsars: average radiation flux at different frequencies, pulse period, period variations, dispersion measure, rotation measure, pulse equivalent width, and many others. The enormous number of pulsar data of different kinds that have been collected provide extensive opportunities for their statistical use. Pulsars deserve to be considered as probes of the interstellar medium, since their distances, determined from their dispersion measures DM, are assumed to be more or less reliable for a large sample of these objects. The main uncertainties in the procedure of determination of pulsar distances are related to the inadequate knowledge of the electron density distribution in the Galaxy.

In the present paper we bring the results mainly obtained in Andreasyan and Arshakian (1993). We study the possibility of determining the luminosities of pulsars using the semiempirical relation between their luminosities, periods and time variation of periods (Andreasyan and Arshakian, 1993; Vivekanand and Narayan, 1981; Stollman, 1987). It gives the possibility to determine so called semiempirical distances for all pulsars. These distances are independent of the distribution of interstellar free electrons and can be used for the study of the electron density distribution in the Galaxy.

2. Radio Luminosities of Pulsars

It is generally accepted that pulsars radiate due to the loss of rotational energy from the neutron stars. This leads to slowing of the pulsar's rotation or an increase

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in the pulse period. The period P and its time variation P′ are among the well-studied observational parameters of pulsars. The bolometric luminosity of a pulsar obviously must depend on the total rotational energy of the neutron star, determined from P, and the slowing rate, which depends on P′ (Gunn and Ostriker, 1970). We use the simplest dependence of radio luminosity L upon the period P and its time variation P′, as used in Andreasyan and Arshakian (1993) and Vivekanand and Narayan (1981).

$$L = \gamma P^{\alpha} P'^{\beta}, \tag{1}$$

where α, β and γ are parameters that are as yet unknown. Since the most complete data in pulsar catalogs are given at 400 MHz, we shall use the flux densities of pulsars at that frequency. We use the following procedure for determination of independent 'semiempirical' distances of pulsars: Using the known distances of pulsars from dispersion measures DM, and flux densities S_{400} at 400 MHz, we estimate the radio luminosities of pulsars. From equation (1) we find the parameters α, β, and γ, that must be universal for all pulsars or for various groups of pulsars chosen from some classification. If we already have these parameters for all or various groups of pulsars, the independent or 'semiempirical' radio luminosities and distances can be determined using equation (1) and the observed flux densities. These distances for each pulsar will differ more or less from those estimated using their dispersion measures, but they will be free from the systematic errors which arise from the inadequate knowledge of the electron density distribution in the Galaxy when we use the method of dispersion measures. So these 'semiempirical', or independent distances can be used for the estimation of the electron density distribution in the Galaxy using the pulsar's dispersion measure data. In this work we show that this procedure works well, and can be used side by side or together with the well-known method of Taylor and Cordes (1993).

Using the flux density data for pulsars, from relation (1) we have

$$R^2 S_{400}\, W/P = \gamma P^{\alpha} P'^{\beta}, \tag{2}$$

where R is the pulsar's distance and W is the equivalent pulse width. The ratio W/P in Equation (2) will take into account the fact, that we view pulsars at some angle from the pulse beam axis. Equation (2) is convenient in that, by taking its logarithm, we obtain a linear equation in α, β, and $\log(\gamma)$ individually for each pulsar in the form

$$\log(R^2\, S_{400}\, W/P)_i = \log(\gamma) + \alpha \log(P)_i + \beta \log(P')_i, \tag{3}$$

where i = 1, 2, . . ., N. We thus obtain a system of N linear equations (N is the number of pulsars used) containing three unknowns, $\log(\gamma)$, α, and β, which is solved by the least squares method. Calculations for all pulsars and for separate groups, separated by period: p<0.7 sec and P>0.7 sec, (see Malov (1989) and Arshakian (1991)) are given in Table I. The results of this part of the work are similar to the

TABLE I

P(sec)	$\lg\gamma$	α	β
All	8.3	−1.4	0.33
<0.7	10.0	−0.6	0.43
>0.7	6.7	−2.1	0.23

results of Andreasyan and Arshakian (1993), Vivekanand and Narayan (1981) and Stollman (1987)

Using the values given in Table I, we have estimated the so-called 'semiempirical" or independent distances for every pulsar. These distances, as was expected, sometimes differ from the known distances more than 2 times, but they have a remarkable tendency: Our distances are less than the known distances at the directions to the centre of the Galaxy, and are more than these at the anticentre directions. This result is in good agreement with the results of Taylor and Cordes (1993), obtained from the study of another sort of data. This result can be explained if we suggest that in old models of interstellar electron density distribution, the electron density was overestimated at the anticentre directions and underestimated at the centre directions of the Galaxy. This is an expected result, and therefore we suggest that our new independent distances can be used for the study of the interstellar electron density distribution in the Galaxy.

3. Electron Density Distribution in the Galaxy

The study of the large-scale distribution of free electrons in the Galaxy is of very great theoretical (in the theory of the turbulent dynamo in the Galaxy, for example) and practical importance (determining pulsar distances from their DM- dispersion measures). It is well known that free electrons are distributed very unevenly in the Galaxy. This is associated mainly with the presence of H I and H II regions in the Galaxy. Despite these inhomogeneities in electron distribution in the Galaxy, however, larger structural features probably exist, and this section is devoted to a study of them. Using equation (2), values of α, β, γ from Table I and observed values of S_{400}, W, P and P' we have determined independent distances R_T for each pulsar. From the equation

$$DM = \int n_e dr = \tilde{n}_e R, \tag{4}$$

substituting R_T for R, we find values of $\tilde{n}_e$ – the average electron density toward each pulsar. The distributions of $\tilde{n}_e$ over Galactic longitude l, obtained for the sample of all pulsars, is given in Figure 1.

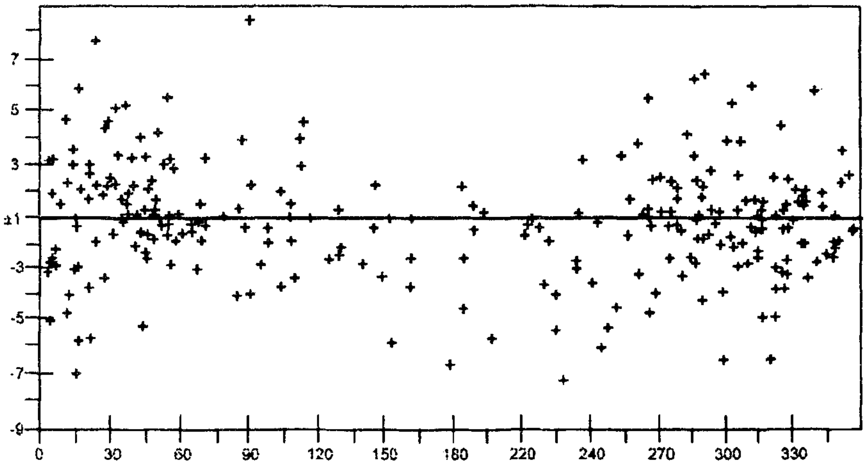

Figure 1. The mean relative electron density as a function of Galactic longitude.

For clarity, instead of $\tilde{n}_e$ in the graph we use the dimensionless quantity $\tilde{n}_e$ / (0.03 cm^{-3}), or its reciprocal taken with a minus sign for $\tilde{n}_e < 0.03$ cm^{-3}. It is clear from the figure, that toward the Galactic anticenter the values of $\tilde{n}_e$ are mainly considerably lower than the average of 0.03 cm^{-3}, while toward the Galactic center the values of $\tilde{n}_e$ are higher than 0.03 cm^{-3}. Since such a result could be expected, the values of R_T and $\tilde{n}_e$ obtained above are fairly reliable statistically and may contain information about the electron density distribution in the Galaxy. This provides a basis for using $\tilde{n}_e$ to study the dependence of electron density on Galactocentric distance R_c and on pulsar distance z above the Galactic plane.

We analyzed functions of the types

$$n_e(R_c,z) = n_1 + n_0 e^{-z/h} \, (10\mathrm{kpc}/R_c)^{\alpha}, \tag{5}$$

$$n_e(R_c,z) = n_1 + n_0 e^{-z/h} \exp[R_c\text{-}R_0/\sigma]^{\,2}. \tag{6}$$

Instead of $n_e(R_c,z)$, we use the average values $\tilde{n}_e$ for individual pulsars. We find the parameters n_1, n_0, h, σ, α, and R_0 from numerical calculations. We take the Sun's distance from the center of the Galaxy to be 10 kpc.

We must note that Equations (6) and (5) differ qualitatively mainly by the fact that there is no maximum with respect to R_c in (5), whereas there is a maximum at R_c=R_0 in (6). The z dependence is the same in the two equations. Calculations from Equation (5) showed that α is negative in the sample of pulsars with R_c<9 kpc ($\alpha = -1.5$), while it is positive for those with R_c>9 kpc ($\alpha = 3.5$). This means that $n_e(R_c,z)$ has a maximum near R_c = 9kpc. The same conclusion can be obtained using the Equation (6). The calculations yield

$$n_0 = 0.052 \text{ cm}^{-3},\ n_1 = 0.005 \text{ cm}^{-3},\ h = 0.7 \text{ kps},\ R_0 = 9 \text{ kps},\ \sigma = 2.9 \text{ kpc}.$$

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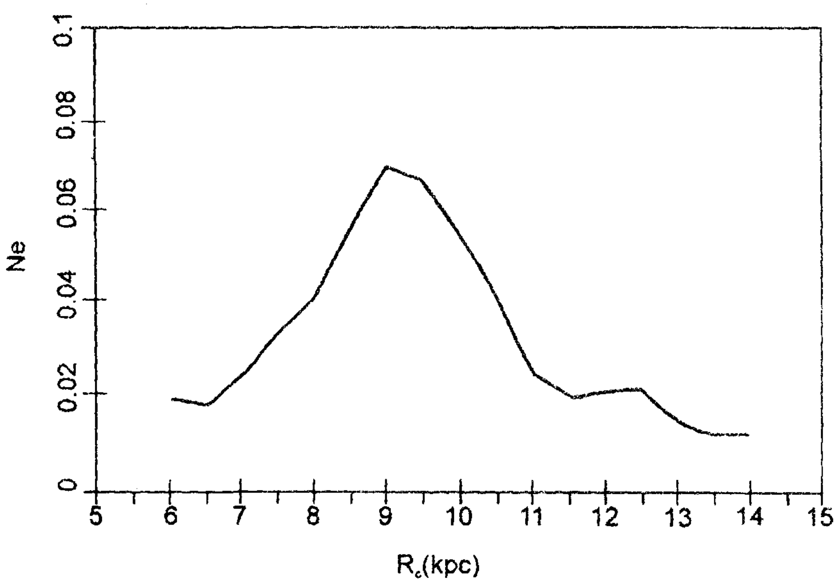

Figure 2. The mean electron density versus Galactocentric distances.

In Figure 2 is shown the distribution of $\tilde{n}_e$ with respect to Galactocentric distance R_c obtained without using Equations (5) and (6).

In all cases the maximum of the distribution of electron density is near R_c = 9 kpc or near the Sagittarius Galactic arm (Georgelin and Georgelin (1976). In this region $n_e = 0.057$ cm^{-3}. In the Galactic plane near the Sun $n_e = 0.046$ cm^{-3}. A tendency for the electron density to increase near the Perseus arm (R>12kpc) is noted, and a weak tendency is seen for the equivalent half-thickness h (see equations (5) and (6)) of the electron layer to decrease toward the center of the Galaxy.

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