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Invited review

ON THE GALACTIC DISTRIBUTIONS OF RADIO PULSARS AND PLASMA DENSITY

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SUMMARY: A brief review of distance measurement methods for some astronomical sources is presented. Galactic plasma density distribution as related to the distribution of radio pulsars is discussed and a method for constructing relations between dispersion measure and distance for Galactic radio pulsars in small solid angle intervals is described. Dispersion measure – distance relations for radio pulsars based on this approach in the Galactic longitude and latitude intervals of $\Delta l = 0^\circ \pm 2^\circ$ and $\Delta b = 0^\circ \pm 2^\circ$ are displayed and comparisons are made with the predictions of the two commonly used models.

Key words. pulsars: general - ISM: structure - plasmas

1. INTRODUCTION

Astronomical observations are fundamentally different as compared to laboratory experiments. In the former case, it is not possible to change the physical conditions of the objects under examination nor to fix their physical parameters, whereas in the latter case, controlled experiments can be done. Even the whole set-up can be changed or the object under examination can be replaced with another, more suitable one and the measurements can be repeated under more or less desired conditions. On the other hand, the maximum values of physical variables that can be attained and maintained for long time intervals are highly limited in laboratory conditions. This fact is especially important in checking and finding the limitations and the boundaries of applicability of some fundamental theories in physics. Checking the limit of Einstein's theory of gravitation for strong gravitational fields is not possible in laboratory experiments done on Earth. The only hope to have some progress in this area of exploration is related to indirect observations of black holes.

Neutron stars are next to black holes in having extremely high values of some physical quantities, especially the density and the magnetic field, and they give the advantage of direct observations. The main difficulty in determining some of their intrinsic and extrinsic properties is due to the fact that determining the distances to astronomical objects is a complicated problem in many cases. The neutron star distances need to be known accurately throughout the Galaxy for example to calculate their radiative power.

There are some standard methods of distance measurements applicable to a large number of astronomical objects. Spectroscopic parallax is one of them. However, it can only be used for ordinary stars by classifying them based on different phases of thermonuclear evolution i.e. reactions in their cores. Trigonometric parallax is another standard method to measure distances with high precision but only for nearby sources (up to about 1 kpc from the Sun).

Observations of supernovae type Ia, used as standard 'candles', and redshift measurements provide distances to galaxies which is important in cosmology, but these methods do not supply information on the distributions of different types of sources within the galaxies. Recent studies on supernovae type Ia (see e.g. Moreno-Raya et al. 2016 and references therein) also point out to the possibility that these sources may not be as standard as we used to assume and it may be needed to make some subclassifications based on the metallicity and the single – double system scenarios.

Some general relations between visual absorption (A_V)[1], and neutral hydrogen column density (N_H), which is calculated from the X-ray absorption, are given in the literature based on observational data of supernova remnants (SNRs), X-ray binaries, molecular (dust) clouds and HI clouds (Reina and Tarenghi 1973, Gorenstein 1975, Predehl and Schmitt 1995, Guver and Ozel 2009). In principle, the measured N_H values of X-ray sources or the measured A_V values of optical sources can be used to put limits on the distances using such relations. However, there are some issues related to these relations. Both N_H and, in particular, A_V values for SNRs are position dependent and can vary significantly within a single SNR due to both intrinsic and extrinsic contributions to N_H and A_V. Similarly, X-ray binaries can have considerable intrinsic N_H, comparable to or even exceeding the contributions to N_H of HI clouds in some cases (see e.g. White et al. 1995, Ankay and Guseinov 1998). Changes in the surface temperature of companion stars in X-ray binaries due to mass loss or effects of irradiation and gravitation of the primary component increase the uncertainty in the A_V values. HI clouds and especially dust clouds have inhomogeneous and anisotropic distributions in the Galactic disk with different scale heights (see e.g. Diplas and Savage 1994a,b, Fruscione et al. 1994, Levine et al. 2006, Hou et al. 2009, Wienen et al. 2015). Some attempts to improve this method were made in the past (Aydin et al. 1997, Ankay and Guseinov 1998) constructing $A_V - N_H$ relations for different solid angle intervals as a function of distance using A_V values of ordinary stars and N_H values of some X-ray sources. Yet, the uncertainties in the distances obtained by this method are still large. As the number of observed clouds, A_V measurements of ordinary stars and N_H measurements of X-ray sources increase, the uncertainties will surely decrease, but this method may never become a standard one because of the significant discrepancy between the two distributions.

For the SNRs formed as a result of core-collapse supernova explosions (see Yazgan 2007 for a review on core-collapse supernovae) producing neutron stars and possibly black holes, there are two basic approaches to distance determination; constructing Galactic rotation models and establishing surface brightness versus linear diameter $(\Sigma - \mathrm{D})$ relations. The former method is a generally applicable one which can be used as a rule for any astronomical object if its radial speed is measurable. The model requires two parameters: the distance of the Sun from the Galactic center and the rotational speed of the Sun around the Galactic center. This method has two major disadvantages. In directions towards the Galactic center, the radial speed corresponds to two possible distances; one beyond the center and the other closer to the Sun than the Galactic center. The orbital speed and the distance of the Sun from the Galactic center adopted differently in the literature (see e.g. Hou et al. 2009, Reid et al. 2014) leads to differences in the distance of the same astronomical object on the order of 100 pc to 1 kpc. The other general distance determination method applicable for Galactic SNRs (excluding plerionic types which is only about 3% of all the Galactic SNRs observed up to date) is to construct relations between their surface brightness and diameter values (e.g. Guseinov et al. 2003a, Pavlović et al. 2013, 2014). Eventually, these relations may effectively classify SNRs based on some intrinsic (e.g. supernova explosion energy) and extrinsic (e.g. density distribution in the ambient medium) parameters. Different types of the supernovae should also be considered in relation to these parameters which is not a trivial problem (see Ankay et al. 2007 for a review). This method was also applied to Galactic planetary nebulae (Vukotić and Urošević 2012).

2. GALACTIC LOCATIONS OF RADIO PULSARS RELATED TO THE DISTRIBUTION OF PLASMA DENSITY

Neutron stars have various types, each type having different observational characteristics. Overall, they produce both thermal and non-thermal radiation covering the whole electromagnetic spectrum. One particular type of neutron stars, namely magnetars are observed to experience bursts at gamma-rays and X-rays, sometimes on as small as millisecond timescales and have surface magnetic fields 1-3 orders of magnitude higher than the conventional values (10^{12} – 10^{13} G) measured for X-ray pulsars in close binaries from the cyclotron lines and also deduced from measurements of spin period (P) and spin period change $(\dot{P})$ of ordinary radio pulsars.

[1] A_V is related to the optical extinction (E(B-V)) with $A_V = \beta$ E(B-V) where β depends on the number and density of clouds in the line of sight (in general $\beta = 3.0$-3.2 but it gets some larger values in some directions)

Neutron stars can basically be modelled as spherically symmetric rotating magnetic dipoles including plasma in their magnetospheres which can be supplied by local surface electric fields (Tagieva et al. 2008) and which is accelerated to produce synchrotron emission (Shapiro and Teukolsky 1983). This is the main reason why the radio pulsar is the most frequently observed type of neutron stars, despite the fact that the selection effects, mainly the distribution of luminosity and the beaming factor, decrease the number of observable radio pulsars considerably as compared to X-ray pulsars. The radio background radiation must also be considered for dim pulsars in the Galactic longitude interval $\Delta l = 0° \pm 60°$ beyond 6-7 kpc (Ankay et al. 2004). It must also be noted that most of the neutron stars are either isolated or members of wide binary systems (for which the effects of the secondary components are not significant) due to asymmetrical core-collapse supernovae as the high values of their measured space velocities (250-300 km/s) suggest (Allakhverdiev et al. 1997, Hansen and Phinney 1997) together with the observational fact that most of them are observable at radio frequencies as neutron stars are not observable as radio pulsars in X-ray binaries where they accrete matter. The number of old recycled ms pulsars in close binaries which evolve through the X-ray binary phase (Bisnovatyi-Kogan and Komberg 1976) must also be much smaller than the number of isolated ones based on the observational data.

There is only one generally applicable method to determine distances of radio pulsars from the Sun based on their pulsed emission at low frequencies. As the radio waves pass through the Galactic plasma (mainly HII-regions, SNRs and the low-density plasma distributed both within the spiral arms and between them), lower frequency waves tend to delay more. The group speed of an electromagnetic wave at frequency f propagating through homogeneous and isotropic plasma is (Ginzburg 1970):

$$V_g = c\sqrt{1 - \left(\frac{f_p}{f}\right)^2}, \quad (1)$$

where f_p is the plasma frequency which depends on the number density of free electrons in the plasma:

$$f_p = \sqrt{\frac{4\pi n_e e^2}{m_e}} \approx 9 \times 10^3 n_e^{1/2} \text{ Hz}, \quad (2)$$

where n_e is the electron number density.

The difference in the arrival times for two different frequencies of the same pulse (both much greater than the plasma frequency, f_p) is then approximately (Lipunov 1992):

$$\Delta t = t_2 - t_1 \approx \frac{e^2}{2m_e c}\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right) \text{ DM}, \quad (3)$$

where

$$\text{DM} = \int_0^d n_e dr \quad (4)$$

is the dispersion measure (d is distance from the pulsar to the Sun).

DM measurements are available for 97% of all the radio pulsars observed up to date with high precision. There are 2457 pulsars with measured DM out of a total number of 2536 (ATNF 2016). Knowing the free electron number density as a function of distance for a particular radio pulsar in some direction should be enough to determine its distance from the Sun. At first sight, it may seem reasonable to adopt average values for the electron density for a few directions as the distribution of plasma should be relatively more homogeneous and isotropic as compared to distributions of both molecular and HI clouds which was partially confirmed by up to date observations (Diplas and Savage 1994a,b, Fruscione et al. 1994, Paladini et al. 2003, 2004a,b, Levine et al. 2006, Hou et al. 2009, Reid et al. 2014). Yet, one must still consider some significant deviations from homogeneity for the Galactic plasma distribution when adopting distances for pulsars located in front of or behind each Galactic arm and the Galactic bulge as well as in some Galactic longitude intervals close to the plane (Yazgan et al. 2006). The locations, thicknesses, and scale heights of the Sagittarius, Perseus, Carina, Scutum, Crux, Norma, Local and Outer arms are known observationally with relatively small uncertainties (Georgelin and Georgelin 1971, 1976, Russeil 2003, Hou et al. 2009, Xu et al. 2013, Zhang et al. 2013, Choi et al. 2014, Sato et al. 2014, Wu et al. 2014, Reid et al. 2014, Hachisuka et al. 2015, Wienen et al. 2015). The Galactic arm structure in the other half of the Galaxy is basically unknown, though 3-4 arms were modelled for regions beyond the center by extrapolation using the locations and shapes of nearby ones (see e.g. Georgelin and Georgelin 1976, Russeil 2003, Hou et al. 2009).

The rotation measure (RM) is also used by some authors in addition to DM to determine pulsar distances. The angle of rotation along the propagation path for the polarization plane of a linearly polarized wave due to Faraday rotation is (Ginzburg 1970, Manchester and Taylor 1977):

$$\Delta\phi = \frac{e^3}{2\pi m_e^2 c^2 f^2}\int_0^d n_e B \cos\theta dr, \quad (5)$$

where B is the magnetic flux density and θ is the angle between the line of sight and the direction of the interstellar magnetic field. The angle of rotation is related to the rotation measure (RM) for wavelength λ of the signal as

$$\Delta\phi = \text{RM}\lambda^2 \quad (6)$$

where

$$\text{RM} = \frac{e^3}{2\pi m_e^2 c^4}\int_0^d n_e B \cos\theta dr. \quad (7)$$

This can be combined with the DM equation (Eq. 4) to get

$$\langle B\cos\theta\rangle = \frac{\int_0^d n_e B\cos\theta dr}{\int_0^d n_e dr} = 1.232 \text{ RM/DM}, \quad (8)$$

where the units are μG for B, rad/m^2 for RM and pc/cm^3 for DM. If the average value of the magnetic field of the interstellar medium along the line of sight is known, the distance can be found using the measured values of DM and RM. As the distribution of magnetic field in the interstellar medium depends on the plasma distribution, the last equation does not significantly improve the distance determination of radio pulsars. Moreover, measured RM values are available for only 689 pulsars out of 2536 (ATNF 2016).

In principle, knowing the Galactic 3D distribution of the plasma practically gives the Galactic 3D radio pulsar distribution so that the observational data on the Galactic arm structure (at least for the half of the Galaxy where the Sun is located) give valuable information on distances of the radio pulsars located close to the plane, especially the young ones with ages less than about 5×10^5 years. Similarly, knowing the distribution of radio pulsars may give the distribution of plasma density. Independent distance measurements of some radio pulsars by trigonometric parallax or from their physical connections to SNRs and stellar clusters may provide valuable information on the plasma density distributions in their lines of sight up to their distances.

There are some semi-empirical models (Taylor and Cordes 1993, hereafter TC93; Cordes and Lazio 2003a,b) and simulations of the Galactic distribution of pulsars (see e.g. Greiner et al. 2016). TC93 modelled the 3D free electron distribution based on a modification of the Galactic arm structure given by Georgelin and Georgelin (1976). Distances of 553 pulsars were derived by TC93 estimating distance uncertainties up to about 25% for most of the known pulsars. Out of the 553 pulsars in the TC93 sample, 134 of them have large, overestimated lower limits on their distances (Cordes and Lazio 2003a). The ATNF pulsar catalogue uses TC93 distances for most of the pulsars. It lists 41 pulsars with d>30 kpc according to TC93, 38 of which have adopted distances of 30 kpc in ATNF catalogue and the remaining three pulsars were assumed to be located at 8.3 kpc (J1745-2900), 8.4 kpc (J1119-6127) and 10 kpc (J2022+3842). All of these pulsars would be more luminous than the Crab pulsar at 1400 MHz if the lower limit of 30 kpc were adopted. For J1119-6127, the 1400 MHz luminosity is comparable to that of Crab's if the ATNF adopted distance of 8.4 kpc is used, while for J1745-2900 and J2022+3842 no flux measurements at this frequency is available. Only 2 out of these 41 pulsars have measured flux at 400 MHz. One of these 2 pulsars must have an order of magnitude larger luminosity and the other must have one third of Crab's luminosity for d=30 kpc.

Based on TC93 model, 24 pulsars have lower limits on their distances in the range 15-30 kpc and these lower limits are still adopted as actual pulsar distances in the ATNF catalogue for all of them except J0248+6021 which has an adopted distance of only 2 kpc. Among these pulsars with d>15 kpc according to TC93, 17 of them must then be more luminous than the Crab pulsar and 3 of them comparable to Crab at 1400 MHz (the remaining 4 pulsars do not have measured flux at this frequency). J0248+6021 has luminosity comparable to Crab's if d=2 kpc. There are 6 pulsars with measured flux at 400 MHz for d>15 kpc based on TC93, 4 of which must be more luminous than and 2 of which must be comparable to Crab.

Note that none of these pulsars with d>15 kpc according to TC93 is located in LMC nor SMC. In fact, TC93 based pulsar distances in LMC and SMC as displayed in the ATNF catalogue include lower limits as small as about 3-3.5 kpc and 2.4-2.5 kpc, respectively, whereas the latest adopted distances given in the ATNF catalogue are 49.7 kpc for LMC and 59.7 kpc for SMC.

About 25% of the pulsars in the TC93 sample have overestimated distance values as derived from this model which was also pointed out by Cordes and Lazio (2003a) and Yazgan et al. (2006). This must be partially due to incorrect modelling of the Galactic arm structure. More importantly, the plasma distribution was assumed to be much more uniform in the central directions than it actually is, neglecting the significant effect of the presence of plasma in the Galactic central region on the determination of distances for pulsars with large values of measured DM. As a result of overestimating the distances, more distant pulsars appear to have larger distances from the Galactic plane and have higher space velocities in TC93 as criticized by Yazgan et al. (2006).

Cordes and Lazio (2003a,b) introduced an improved version of TC93 model (hereafter NE2001) again mainly based on the Galactic arm structure represented by Georgelin and Georgelin (1976) with modifications. They constructed a mathematical tool to get the pulsar distance by entering its Galactic coordinates and the measured DM or entering the distance together with the coordinates to get the corresponding DM with relatively small uncertainties for most of the pulsars. Such a method would be most helpful if the exact locations of HII regions and SNRs and the density distributions of plasma within these extended sources and the Galactic central region were known precisely.

For the Crab pulsar, the distances from the models are 1.7±0.3 kpc (NE2001), 2.5 kpc (TC93) and the ATNF adopted distance is 2 kpc. The Crab's distance is adopted as 2 kpc by almost all the authors with a possible uncertainty of 20-25% so that the predicted distances from the two models are more or less compatible. In the case of Vela pulsar, the situation is more complicated, though it is certainly a more nearby pulsar than the Crab: 236^{+4}_{-3} pc (NE2001), 610 pc (TC93) and 280 pc (ATNF adopted), the last value is based on parallax measurements: 280^{+60}_{-50} pc (Caraveo et al. 2001) and 290±20 pc (Dodson et al. 2003). The errors and possibly the distance given by NE2001 are underestimated compared to the parallax measurements. A more important point is that if the distance of Vela is about 250-300 pc, its position on the $\Sigma - D$ diagram will be close to the SNR SN1006 (Guseinov et al. 2003a), which is unlikely as the progenitor of Vela was most probably a massive star exploded as a type II supernova as strongly suggested by observations of the Vela SNR which lies in a very dense medium. However, SN1006 was probably a type Ia explosion as this SNR is located at about 0.5 kpc from the Galactic plane in a low density medium and no pulsar of any type nor any sign indicating the presence of a pulsar (pulsar wind nebula or bow-shock) was observed in it (Yazgan et al. 2006, Ankay et al. 2007).

For most of the Galactic HII regions (the total number of which is 8405 including the unconfirmed ones), the distances and the plasma densities are unknown (WISE 2016). Uncertainties in the distances of most Galactic SNRs are not less than 30% (Guseinov et al. 2003a, Yazgan et al. 2006). Using equations with many parameters to represent the Galactic plasma distribution leads to systematic overestimations or underestimations of the distances for most of the radio pulsars as in the cases of the TC93 and the NE2001 models, especially for distant pulsars in the first and the fourth quadrants of the Galaxy where the lines of sight pass through several Galactic arms and the Galactic bulge for central directions.

Instead of constructing such semi-empirical models for the plasma density distribution or for the pulsar distribution throughout the Galaxy without making fits, it is better to divide the total solid angle covering all directions into as small solid angle intervals as statistically possible to get DM – distance relations with relatively small fluctuations for each such interval using directly the observational data. Based on the fact that the distribution of radio pulsars and the distribution of their measured DM values related to the plasma distribution are strongly correlated in narrow intervals of Galactic longitude and latitude, one can use the independent distance measurements of some well observed pulsars to get the DM distribution in such small intervals of solid angle and in turn use this information to clarify the distance distribution of the other pulsars in the same interval taking also into consideration some basic criteria which will be presented in the next section. This would work best in the Galactic longitude interval $\Delta l = 0° \pm 90°$ where most pulsars are located.

Spatial distribution of radio pulsars and its relation to the plasma density distribution were examined in some earlier works (Guseinov and Kasumov 1978, 1981, Gailly et al. 1978). Later, some models on using the DM values together with some basic criteria based on empirical facts to determine locations of pulsars in different intervals of longitude and latitude were constructed, improving the pioneering work by Guseinov and Kasumov (1981) as a result of the large increase in the number and quality of the observational data (Gok et al. 1996, Guseinov et al. 2002, Yazgan et al. 2003, 2006). The statistical implications on radio pulsars based on the distances derived from these models are presented by Guseinov et al. (2003b, 2004a).

As the number of observed pulsars and their data increased significantly in the last decade (more than 2500 pulsars are listed in the ATNF catalogue most of which were detected as radio pulsars with measured DM values) and since some recent observations on the distributions of HII regions and molecular and HI clouds (Levine et al. 2006, Hou et al. 2009, Xu et al. 2013, Zhang et al. 2013, Choi et al. 2014, Sato et al. 2014, Wu et al. 2014, Reid et al. 2014, Hachisuka et al. 2015, Camargo et al. 2015, Wienen et al. 2015) gave much better information on the Galactic arm structure and the plasma in the Galactic central region as compared to the earlier works, such a model can now be reconstructed to essentially improve the pulsar distances and the Galactic plasma density distribution. The method we use in an ongoing work on constructing such a model (Ankay et al. 2007) and some of our preliminary results including the ones on the pulsars in the Galactic central directions are presented below together with some comparisons with the results of TC93 and NE2001.

The best distance measurements are done by using trigonometric parallax as the positions can be measured highly accurately, especially for radio sources. The downside of this method is that it can not be applied to distant objects as most radio pulsars are. Yet, there is an increase in the number of distance measurements of radio pulsars by trigonometric parallax recently (Matthews et al. 2016, Reardon et al. 2016) in addition to some older measurements (Gomez et al. 2001, Brisken et al. 2002, Hotan et al. 2006, Chatterjee et al. 2009, Deller et al. 2009, Verbiest et al. 2009, Gonzalez et al. 2011, Abdo et al. 2013 and references therein). Since the trigonometric parallax method gives highly accurate distance measurements in most cases, the new measurements increased the number of calibrator pulsars which can be used in constructing DM – distance relations. Another way to adopt the calibrators is to check physical associations between radio pulsars and SNRs, globular clusters and, in some rare cases, open clusters and OB associations. Radio pulsars detected in LMC and SMC may also be used as calibrators as the distances of them are accurately measured. However, the plasma distribution in LMC and SMC (see e.g. Lehner and Howk 2007) should also be taken into consideration which is not well known. Such pulsars may still be used by taking their DM values as upper limits when making fits relating the distance to DM.

Timing parallax and X-ray measurements of radio/X-ray pulsars can also be used to determine their distances, but in general with large uncertainties (White et al. 1995, Matthews et al. 2016, Reardon et al. 2016).

The Galactic arm structure was examined in a large number of observational studies as cited above mainly based on the distributions of the giant HII regions and molecular clouds observed up to date. A list of Galactic SNRs is presented by Green (2014, Galactic SNRs catalogue) which can be used as a primary source together with the data and remarks given by Guseinov et al. (2003c, 2004b,c) in addition to collecting recent observational data on SNRs. Recently measured high DM and high RM values for the pulsars in the central directions (Schnitzeler et al. 2016) should also be taken into account in constructing DM – distance relations for Galactic central directions.

3. BASIC CRITERIA FOR CONSTRUCTION OF DM – DISTANCE RELATIONS

Based on the available observational data, assuming that the main contribution to the measured DM values is mainly due to the plasma in the HII regions, SNRs and possibly the Galactic central region, the following criteria must be considered in constructing DM – distance relations (see also Guseinov et al. 2002, Yazgan et al. 2003, 2006):

1) A significant number of high luminosity radio pulsars lie in the interval $\Delta l = 0° \pm 40°$ covering a large portion of the Galaxy. It must also be noted that the radio luminosity (synchrotron emission) does not depend on the location of the pulsar nor on its age and most of the pulsars have low radio luminosity (Guseinov et al. 2003b, 2004a). In fact, more than half of the high luminosity radio pulsars at 1400 MHz and 400 MHz do not lie in this longitude interval even if corrections are made for the overestimated pulsar distances adopted in the ATNF catalogue (ATNF 2016). Some of these high luminosity pulsars are even located in anti-center directions (e.g. J2238+6021 with l=107.14° and J0341+5711 with l=144.37°). Making comparisons with Crab pulsar's luminosity is helpful in adopting pulsar distances in order to prevent overestimations in most cases.

2) Deviations of the arms from the Galactic plane in some longitude intervals must be considered in adopting distances (Berdnikov 1987, Efremov 1989, Russeil 2003, Hou et al. 2009, Xu et al. 2013, Zhang et al. 2013, Choi et al. 2014, Wu et al. 2014, Sato et al. 2014, Reid et al. 2014, Hachisuka et al. 2015, Wienen et al. 2015). The pulsar distances from the Galactic plane (and from the deviated regions) for pulsars having similar ages must be comparable to each other up to the characteristic age ($\tau = P/2\dot{P}$) of about 10^7 years, beyond which τ is no longer related to the real age (Guseinov et al. 2004d).

3) Young pulsars with $\tau < 5 \times 10^5$ years must be located in or close to the star formation regions (molecular clouds, HI clouds, giant HII regions, SNRs, OB associations and open clusters) within the Galactic arms considering the average space velocity of pulsars to be about 250-300 km/s (Allakhverdiev et al. 1997, Hansen and Phinney 1997).

4) The Galactic distribution of free electrons and their number density must be correlated with the locations and density of HII regions, SNRs and OB associations. The correlation must become weaker at larger distances due to the presence of low-density plasma between the Galactic arms. The free electron density must decrease as the distance from the Galactic plane increases in general (the deviations of the arms from the Galactic plane must also be considered) with the plasma distribution becoming more uniform. Therefore, pulsars at larger Galactic latitudes must be located at relatively larger distances as compared to the pulsars at smaller latitudes with similar DM values at the same longitudes.

5) The effect of the presence of plasma in the Galactic central region on determining the distances of pulsars with large DM values in the central directions can be as significant as the combined effect of the plasma within the three spiral arms between the Sun and the Galactic bulge. The effect of the Galactic central plasma can even predominate as seen in the case of magnetar J1745-2900 ($l = 359.94°$, $b =$ -0.05°, DM = 1778 pc/cm^3) unless it is located at a very large distance beyond the center.

6) In adopting distances for radio pulsars for which the line of sight passes through the Galactic arms, the location, thickness and scale height of each arm based on the available observational data should be taken into consideration together with the measured DM values. As the line of sight passes through each arm, there must be an increase in the average free electron density.

4. PRELIMINARY RESULTS FOR RADIO PULSARS NEAR THE GALACTIC CENTER AND SOME COMPARISONS WITH THE TC93 AND THE NE2001 MODELS

Fig. 1 displays DM – distance relations for the Galactic central directions in the longitude and the latitude intervals $\Delta l = 0° \pm 2°$ and $\Delta b = 0° \pm 2°$ by Ankay, Yazgan and Kutukcu (Ankay et al. 2017, hereafter AYK) as part of an ongoing work on a sample of all the 2457 radio pulsars with measured DM. The pulsar distances from the models by TC93 and NE2001, and the adopted distances presented in the ATNF catalogue are also shown in Fig. 1 in order to make comparisons. As seen in the figure, the slope for the relations by AYK decreases (i.e. the average free electron density increases) from the Sun up to the Galactic central region gradually, reflecting the effects of the three spiral arms (Sagittarius, Scutum and Norma) between the Sun and the Galactic bulge. There are no observed radio pulsars in the Local arm in these directions. There is a gap in the DM interval

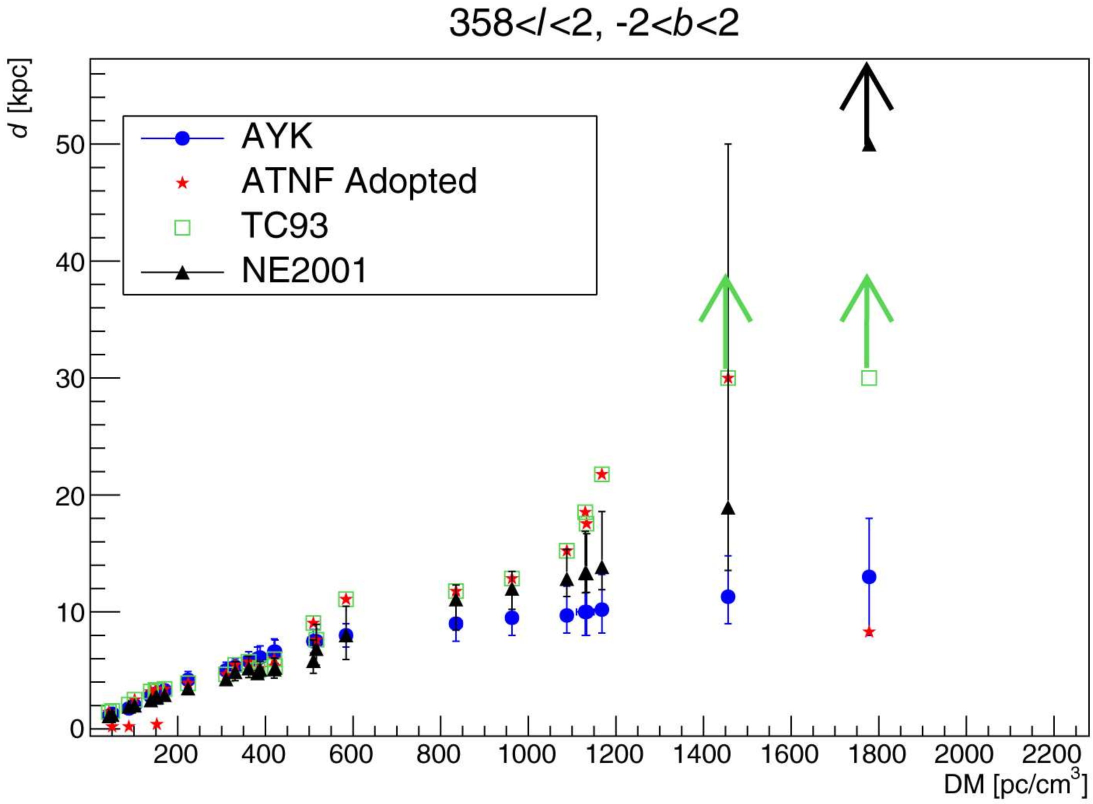

Fig. 1. *DM – distance relations for the pulsars in $\Delta l = 0° \pm 2°$ and $\Delta b = 0° \pm 2°$ intervals. Circles, triangles and squares represent the pulsar distances from the three models by AYK, NE2001 and TC93, respectively. Asterisks display the adopted distances given in the ATNF catalogue where the TC93 model is used as default. Arrows show the lower limits on the distances.*

of about 600 – 800 pc/cm^3 possibly corresponding to the region between the Norma arm and the Galactic bulge. Beyond DM=800 pc/cm^3 the free electron density further increases significantly (about 0.26 per cm^3 on average) mainly due to the presence of possibly dense plasma in the central region (WISE 2016, Schnitzeler et al. 2016) and due to the possible extrapolations of the Sagittarius, Perseus and Norma arms (see e.g. Russeil 2003, Hou et al. 2009).

Up to about 4-5 kpc from the Sun, the distances based on the three models (i.e. AYK, NE2001 and TC93) are in agreement, but the adopted distances given in the ATNF catalogue for three pulsars are comparably too small (0.2-0.4 kpc) leading to a large free electron density in the nearby medium of the Sun in the Galactic central directions (Fig. 1). For several pulsars located at about 5±1 kpc, the average free electron density becomes very large according to the NE2001 model, larger than the average density for the Galactic central region and beyond. This may be due to ignoring the plasma in the central region and the presence of Galactic arms beyond the center as seen in Fig. 1. As for the distances derived from the TC93 model and adopted in the ATNF catalogue, the situation is similar except the slope increases (free electron density decreases) steeply beyond the center possibly due to the wrong assumption that the plasma distribution is uniform in the other half of the Galaxy beyond the central region where there is no effect of the central plasma or the distant arms.

The location of the magnetar J1745-2900 with the largest DM and RM measured for any pulsar up to date (l = 359.944°, b = -0.047°, DM = 1778 ± 3 pc/cm^3, RM = -66080 ± 24 rad/m^2, Schnitzeler et al. 2016; RM = -66960±50, ATNF 2016) is especially important in Fig. 1. If this pulsar is located at or very close to the Galactic center as concluded by Schnitzeler et al. (2016) due to the closeness of its position to the position of Sgr A (l = 359.944°, b = -0.046°) and its large RM and DM values, the average free electron density would further increase in the Galactic central direction (see Fig. 1).

The DM of the magnetar is about 1.22 times larger than the next largest DM (J1746-2849, l = 0.134°, b = -0.030°, DM=1456 ±3 pc/cm^3, RM = 10104 ± 101 rad/m^2, Schnitzeler et al. 2016). The average RM over 10 epochs for Sgr A was measured by Marrone et al. (2007) as -5.6 ±0.7 × 10^5 rad/m^2 stating that the measurements are consistent with a constant RM value. Marrone et al. (2007) also conservatively give a 3σ upper limit of 2×10^5 rad/m^2 to rotation measure changes.

According to the WISE catalogue of Galactic HII regions (v1.4, 2016), there are 73 known HII regions in the Galactic longitude and latitude interval $\Delta l = \Delta b = 0° \pm 2°$, 18 of which were measured to be located at d=8.5 kpc, one of them at d=7.8±0.7 kpc and no distance measurements for the rest given in the catalogue. The linear diameters of these HII regions at such Galactic central distances are in the range from several parsecs up to about 30 pc. The lines of sight of the magnetar and of J1746-2849, which have the largest DM, pass through none of these 73 HII regions even if we assume that all of them are located at d=8.5 kpc. In fact, none of the pulsars with DM $>$ 800 pc/cm^3 displayed in Fig. 1 has a line of sight passing through any one of these known HII regions at d=8.5 kpc.

The total number of all the sources (radio quiet ones, groups, candidates, unknown sources) in the interval $\Delta l = \Delta b = 0° \pm 2°$ listed in the WISE catalogue in addition to the known HII regions, several of which must have linear diameters close to 80-100 pc at d=8.5 kpc, is 451. Some of these sources may intersect the lines of sight of the high DM pulsars and they may include some significant amount of plasma. The problem whether the plasma in the central region significantly affects the DM values is discussed below.

As presented in the ATNF catalogue, there are 58 pulsars with DM $>$ 800 pc/cm^3, none of them located in the anti-center directions ($90° < l < 270°$) and only 8 of them are in the interval $\Delta l = \Delta b = 0° \pm 2°$ as displayed in Fig. 1. Moreover, six of these large DM pulsars are located in the longitude interval $\Delta l = 304° - 313°$ close to the Galactic plane (-1° $< b <$ 0.85°). It is possible that these directions cut through a large portion of the Crux arm (see e.g. Russeil 2003). In fact, there are 37 known HII regions in this interval for most of which the distance is in the range 3.5-8.7 kpc (WISE 2016). Similarly, there are four pulsars with large DM in the interval $304° < l < 307°$, -0.9° $< b <$ 0.85° which possibly covers a large part of the Carina arm and which includes 12 known HII regions in the distance range 3.1-9.7 kpc. The lines of sight for ten such pulsars in the interval $29° < l < 39°$ (all close to the Galactic plane) pass through several arms especially the Sagittarius arm (this interval includes a large number of HII regions at various distances). All the other large DM pulsars lie in the interval $\Delta l = 0°{}^{+24°}_{-29°}$ (except $\Delta l = 0° \pm 2°$) close to the Galactic plane for which the lines of sight cut through up to possibly six arms.

5. SUMMARY AND CONCLUSIONS

We present a short review on the distance determination methods for some astronomical objects. In particular, the radio pulsar distances related to Galactic plasma density distribution are discussed. Two commonly used models on DM – distance relations are examined and an alternative method introduced by Oktay H. Guseinov is described. We conclude that constructing DM – distance relations for small solid angle intervals gives better results compared to semi-empirical models including mathematical expressions with many parameters to give the Galactic plasma distribution in determination of radio pulsar distances.

Finding the distances of pulsars located at large distances in directions towards the Galactic center is most problematic in all models. Although the effect of the central plasma on DM seems to be important, the plasma within the arms should also be considered as significant in directions towards the Galactic center. In other directions, the effects of the arms especially in some longitude intervals cutting through large portions of them in the first and the fourth Galactic quadrants seem to be predominant.

The large DM pulsars in the central directions must be located close to or more likely beyond the Galactic center (d=8.0±0.5 kpc) but definitely not outside the Galaxy. As an exceptional case, magnetar J1745-2900, which is very young (τ = 3400 yr), was probably born and located close to the Galactic center where the free electron density can be very large due to the supermassive black hole, but the possibility that it was born and is still located at one of the Galactic arms beyond the center can not be neglected.

Thanks to the significant increase in the number and quality of the data on radio pulsars, giant molecular clouds, HII regions and SNRs, the relations between DM and distance can further be improved getting much better results on the distributions of both radio pulsars and plasma density in the Galaxy following the method of Guseinov. We continue to work in an ongoing project on this subject.

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О ГАЛАКТИЧКОЈ РАСПОДЕЛИ РАДИО-ПУЛСАРА И ГУСТИНЕ ПЛАЗМЕ

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Прегледни рад по позиву

Представљамо кратак преглед метода за мерење даљине до неких астрономских извора. Дискутује се расподела густине Галактичке плазме и њена веза са расподелом радио-пулсара. Описан је метод за конструисање релације између мере дисперзије и даљине до Галактичких радио-пулсара у малим интервалима просторног угла. Представљена је релација мера дисперзије – даљина за радио-пулсаре заснована на овом приступу, у интервалима Галактичке лонгитуде и латитуде $\Delta l = 0° \pm 2°$ и $\Delta b = 0° \pm 2°$, као и поређење са предвиђањима два најкоришћенија модела.