Probing Milky Way’s hot gas halo density distribution using the dispersion measure of pulsars

Emin Ya. Nugaev* and Grigory I. Rubtsov†
Institute for Nuclear Research of the Russian Academy of Sciences, 117312, Moscow, Russia

Yana V. Zhezher‡
Faculty of Physics, M.V. Lomonosov Moscow State University, 119991, Moscow, Russia and Institute for Nuclear Research of the Russian Academy of Sciences, 117312, Moscow, Russia

A number of recent studies indicates a significant amount of ionized gas in a form of the hot gas halo around the Milky Way. The halo extends over the region of 100 kpc and may be accountable for the missing baryon mass. In this paper we calculate the contribution of the proposed halo to the dispersion measure (DM) of the pulsars. The Navarro, Frenk & White (NFW), Maller & Bullock (MB) and Feldmann, Hooper & Gnedin (FHG) density distributions are considered for the gas halo. The data set includes pulsars with the distance known independently from the DM, e.g. pulsars in globular clusters, LMC, SMC and pulsars with known parallax. The results exclude the NFW distribution for the hot gas, while the more realistic MB and FHG models are compatible with the observed dispersion measure.

Keywords: missing baryons – hot gas – pulsars – dispersion measure

I. INTRODUCTION

“Missing baryons” is one of the long-standing problems of modern astrophysics. The total baryon mass obtained from the cosmic microwave background anisotropy measurements and from the data on the big-bang nucleosynthesis exceeds the mass of the stars, interstellar and intergalactic media [1]. The ratio of the baryon mass to the total mass at high redshifts is estimated with better than 5% accuracy from the Planck data [2]. On the other hand we observe less than the half of these baryons at present.

One of the possible solutions for this problem is that “missing” baryons reside in intergalactic medium (IGM). It is possible that the haloes of the galaxies may be the dominant component of IGM [3]. In this scenario the Milky Way’s halo is a huge bubble of gas with the radius up to 250 kpc [4] which may be produced by the matter accretion from the satellite galaxies and intergalactic medium [4].

Milky Way’s gas halo may be considered as a composition of three general components: cold gas, warm ionized medium (WIM) and hot ionized medium (HIM). The WIM component is produced by strong UV radiation from O and B stars. It mainly consists of the ionized hydrogen (HII regions) and additionally of sulfur, nitrogen and oxygen (SII, NII, OI - OIII lines) [5]. WIM contains 30 % of interstellar medium mass and its temperature is up to 10^4 K. The size of the warm gas halo is about 2 kpc which is similar to the size of the neutral hydrogen component.

The HIM is considered as one of the candidates for the source of all “missing” baryons. An interest for this solution has grown in 2012 after the work of A. Gupta and S. Mathur [12]. Analyzing the data from Chandra X-ray Observatory they examined emission and absorption lines of active galactic nuclei and have found a huge reservoir of ionized gas traced by O V II and O V III absorption lines extending to more than 139 kpc. The mass of the hot gas halo is compatible with the “missing” mass and this may be considered as a solution of the problem.

In this paper we study the contribution of the hot gas halo proposed in [12] to the dispersion measure of the pulsars. The DM is calculated for the case of the three models of halo density distribution and compared to experimental data.

The present paper is organized as follows. First, in Section II we define a dispersion measure and overview the Navarro, Frenk & White (NFW), Maller & Bullock (MB), and Feldmann, Hooper & Gnedin (FHG) density distribution models. Next, in Section III the data set of the pulsars with the distance known independently of the DM is formed. The comparison of the data with the calculations is given in Section IV.

*emin@ms2.inr.ac.ru
†grisha@ms2.inr.ac.ru
‡zhezher.yana@physics.msu.ru
II. METHODS

Electromagnetic waves emitted by a pulsar propagate through the interstellar plasma. The plasma is dispersive, i.e. the lower-frequency radio waves travel slower than the higher-frequency ones. Propagation delay may be calculated as follows [13, 14]:

$$\delta t = \frac{e^2}{2\pi mc^2} DM,$$  \hspace{1cm} (1)

where $DM$ is defined as an integral of the electron density along the propagation line:

$$DM = \int_0^d n_e ds.$$  \hspace{1cm} (2)

Observing the pulsar at multiple radio bands one may measure the time shift between the pulse profiles at these bands with the high accuracy. This gives an instrument to probe free electron distribution in the interstellar medium (ISM).

The calculations of the DM are based on the model of electron distribution in the Milky Way's halo. There are two general models conventionally used in this case [15]: Navarro, Frenk & White and Maller & Bullock.

Navarro, Frenk & White model describes the dark matter mass distribution, derived by simulating N-body system in the Standard Cosmological Model [16]. It approximates equilibrium distribution of dark matter for non-colliding particles:

$$\rho_g^{NFW} (r) = \frac{\rho_0}{x(1 + x)^2},$$  \hspace{1cm} (3)

where $r$ is the distance from Galactic center, $x = r/R_s$, $R_s = R_v/C$, where $R_v = 260$ kpc is virial radius associated with Milky Way's dark matter halo, $C$ is halo concentration.

The two particular cases are considered: density profile may mimic dark matter distribution with its concentration $C_v$, and $C = C_v = 12$, or it obeys low-concentration scenario with $C = 3$. We note, however, that the gas in haloes has non-gravitating mechanism of formation and the density profile for the dark matter is not directly applicable.

The Maller & Bullock model was proposed in 2004 [17]. It describes a gas in hydrostatic equilibrium within the dark matter halo. If hot gas doesn’t radiate significantly, it obeys an adiabatic law with polytropic index 5/3 within the cooling radius $R_c$, $\rho \propto \rho_b^{5/3}$. The dark matter is assumed to follow NFW profile with the $C_v = 12$. The hot gas density distribution is the following:

$$\rho_g^{MB} (r) = \begin{cases} \kappa_1 \left[ 1 + \frac{3.7}{x} \ln (1 + x) - \frac{3.7}{C_v} \ln (1 + C_v) \right]^{3/2}, & r < R_c, \\ \kappa_2 / r^2, & R_c < r < R_v. \end{cases}$$  \hspace{1cm} (4)

The parameter $C_v = R_v/R_s$ takes the value $C_v = 7$ according to [17].

We obtain virial density $\rho_v$ for NFW distribution and constants $\kappa_1, \kappa_2$ for MB distribution from the assumption that a sphere with its center in the Galactic center and radius $R = 260$ kpc contains all the Galaxy “missing” mass:

$$4\pi \int_0^R pr^2dr = 10^{11}M_\odot.$$  \hspace{1cm} (5)

Alternatively, as a realistic hot gas density distribution a numerical model of Feldmann, Hooper & Gnedin [18], based on high-resolution cosmological and hydrodynamical simulations is used. We assume that the hot gas halo contains mainly hydrogen and helium and use the density profile obtained for ionized hydrogen distribution with the normalization as stated above.

The electron number density is directly related to the baryonic density:

$$n_e = \frac{\rho}{m_p} (1 - Y_P/2)$$  \hspace{1cm} (6)

where $m_p$ is a proton mass and $Y_P \approx 0.25$ – helium mass fraction taken from [19].

III. DATA SET

In this paper we analyze pulsars in the Milky Way, in the Large Magellanic Cloud (LMC) and in the Small Magellanic Cloud (SMC). There are no known pulsars in Andromeda Galaxy (M31) yet, but the future observations will likely discover ones [20].

In order to calculate the dispersion measure of a pulsar one needs to know distance from it to the Galactic center. Usually it is calculated from experimental DM, but there are two kind of pulsars with independent distance in the Milky Way: pulsars with measured parallaxes and pulsars in the globular clusters [21].

We analyzed 144 pulsars in 28 globular clusters [22, 23] and 63 pulsars with parallaxes [24]. Within the one globular cluster analytical dispersion measure is the same for all pulsars and experimental one differs insignificantly. The experimental dispersion measure values were picked up from ATNF (Australia Telescope National Facility) Pulsar Catalogue [25]. The data used for Milky Way Galaxy pulsars data are given in Tables II and III. The data for LMC and SMC are given in Table IV. The galactic coordinates for M31 are $l = -21.6^\circ$, $b = 121.2^\circ$ and distance $D = 784.9$ kpc.

IV. RESULTS

The dispersion measure is calculated for each pulsar in our data set within 4 different models: NFW model with $C = 12$ and $C = 3$, MB model and FHG model.
Comparisons of experimental and analytical dispersion measures are shown in Figures 1 and 2, and in Table IV. The predicted DM for Andromeda is given in Table V.

The dispersion measure of the particular pulsar is summed up from the intrinsic DM and from the effect of ISM. In this paper we concentrate only of the contribution of hot gas halo. Therefore, for a viable model the result of calculation may not be greater than the measured values. For the both NFW $C = 3$ and $C = 12$ there are pulsars with model DM greater than the experimental one and therefore for these energy density the model of ionized hot gas halo contradicts to the pulsar data. On the other hand, more realistic MB and FHG models are not excluded with the method of the paper. The predicted DM in these models do not exceed the observed one for all Milky Way, LMC and SMC pulsars.

V. CONCLUSION

The pulsar DM data rule out NFW density model of the hot gas halo for the both cases $C = 3$ and $C = 12$. At the same time more realistic MB and FHG models are not constrained with this method.

In future, the studies using Square Kilometre Array (SKA) may double or triple the known pulsar population [20]. For our study, finding new pulsars on various latitudes and longitudes will provide all-round interstellar medium probe with the higher reliability and accuracy. Moreover, hot gas halos of the nearby massive galaxies may be probed through the Sunyaev-Zel’dovich distortion of the cosmic microwave background radiation [26].

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TABLE I. List of Milky Way globular clusters

| Globular cluster name | Galactic longitude (deg) | Galactic latitude (deg) | Distance (kpc) | DM (cm/pc³) |
|-----------------------|--------------------------|-------------------------|---------------|-------------|
| 47 Tucanae (NGC 104)  | 305.9                    | -44.89                  | 4             | 24.4        |
| NGC 1851              | 244.51                   | -35.04                  | 12.1          | 52.1489     |
| M 53 (NGC 5024)       | 322.96                   | 79.69                   | 17.2          | 24          |
| M 3 (NGC 5272)        | 42.41                    | 78.71                   | 10.4          | 26.4        |
| M5 (NGC 5904)         | 3.86                     | 46.8                    | 8             | 29.6        |
| NGC 5986              | 337.02                   | 13.27                   | 7.66          | 92.17       |
| M4 (NGC 6121)         | 350.97                   | 15.97                   | 2.2           | 62.8633     |
| M13 (NGC 6205)        | 59.01                    | 40.91                   | 7.5           | 30          |
| M62 (NGC 6266)        | 353.57                   | 7.32                    | 6.9           | 114.06      |
| NGC 6342              | 4.9                      | 9.73                    | 8.6           | 71          |
| NGC 6397              | 338.17                   | -11.96                  | 3.4           | 71.8        |
| Terzan 5              | 3.84                     | 1.69                    | 8.7           | 238.5       |
| NGC 6440              | 7.73                     | 3.8                     | 8.4           | 222.8       |
| NGC 6441              | 353.53                   | -5.01                   | 11.7          | 232.2       |
| NGC 6517              | 19.23                    | 6.76                    | 10.6          | 172.98      |
| NGC 6522              | 1.02                     | -3.93                   | 7.8           | 193         |
| NGC 6539              | 20.8                     | 6.78                    | 8.4           | 186.38      |
| NGC 6544              | 5.84                     | -2.2                    | 2.7           | 135.6       |
| NGC 6624              | 2.79                     | -7.91                   | 7.9           | 87.61       |
| M28 (NGC 6626)        | 7.8                      | -5.58                   | 3.7           | 120.1       |
| NGC 6652              | 1.53                     | -11.38                  | 2.49          | 63.35       |
| M22 (NGC 6656)        | 9.89                     | -7.55                   | 3.2           | 89.7        |
| NGC 6749              | 36.2                     | -2.2                    | 7.9           | 192.846     |
| NGC 6752              | 336.49                   | -26.53                  | 4.5           | 33.36       |
| NGC 6780              | 36.11                    | -3.92                   | 7.4           | 199.684     |
| M71 (NGC 6838)        | 56.74                    | -4.56                   | 6.68          | 117         |
| M15 (NGC 7078)        | 65.01                    | -27.31                  | 12.9          | 66.87       |
| M30 (NGC 7099)        | 27.18                    | -48.83                  | 9.2           | 50.07       |
| Pulsar name | Galactic longitude (deg) | Galactic latitude (deg) | Distance (kpc) | DM (cm/pc$^2$) |
|------------|--------------------------|--------------------------|----------------|----------------|
| J0030+0451 | 113.14                   | -57.61                   | 0.28           | 4.333          |
| J0034-0721 | 110.42                   | -69.82                   | 1.03           | 13.76517      |
| J0108-1431 | 140.93                   | -76.82                   | 0.21           | 2.38           |
| J0139+5814 | 129.22                   | -4.04                    | 2.6            | 37.779         |
| J0218+4232 | 130.51                   | -17.63                   | 5.85           | 61.252         |
| J0332+6344 | 145                      | -1.22                    | 1              | 26.7641        |
| J0538+6413 | 148.19                   | 0.81                     | 1              | 57.142         |
| J0437+4715 | 253.39                   | -41.96                   | 0.156          | 2.64476        |
| J0452-1759 | 217.08                   | 34.09                    | 0.3            | 39.903         |
| J0544+5543 | 152.02                   | 7.56                     | 1.18           | 34.495         |
| J0538+2817 | 170.72                   | -1.69                    | 1              | 39.57          |
| J0613-0200 | 210.41                   | -9.3                     | 0.9            | 38.77919       |
| J0630-2834 | 236.95                   | -16.76                   | 0.32           | 34.468         |
| J0659+1414 | 201.11                   | 8.26                     | 0.28           | 13.977         |
| J0720-3125 | 244.16                   | -8.16                    | 0.4            | 70.84          |
| J0737+3039AB | 245.23                  | -4.5                     | 1.1            | 48.92          |
| J0751+1807 | 202.73                   | 21.09                    | 0.4            | 30.2489        |
| J0814+7429 | 140                      | 31.62                    | 0.432          | 5.733          |
| J0826-3350 | 235.80                   | 12.53                    | 1.3            | 40.938         |
| J0826+2637 | 196.96                   | 31.74                    | 0.32           | 19.454         |
| J0835-4510 | 263.55                   | -2.79                    | 0.28           | 67.99          |
| J0922+0638 | 225.42                   | 36.39                    | 1.1            | 27.271         |
| J0958+0755 | 228.91                   | 43.7                     | 0.26           | 2.358          |
| J1012+5037 | 160.35                   | 50.86                    | 0.7            | 9.0233         |
| J1017+7156 | 291.56                   | -12.55                   | 0.26           | 94.22407       |
| J1022+1001 | 231.79                   | 51.1                     | 0.52           | 10.2621        |
| J1023+0038 | 243.39                   | 45.78                    | 1.37           | 14.325         |
| J1034-0719 | 253.7                    | 40.52                    | 0.49           | 14.4852        |
| J1045-4509 | 280.85                   | 12.25                    | 0.23           | 58.1662        |
| J1136+1551 | 241.9                    | 69.2                     | 0.35           | 4.8451         |
| J1209+2453 | 252.45                   | 86.54                    | 0.84           | 9.242          |
| J1300+1240 | 311.31                   | 75.41                    | 0.6            | 16.1665        |
| J1345+0841 | 313.87                   | -8.54                    | 0.33           | 8.3            |
| J1509+5531 | 91.33                    | 52.29                    | 2.1            | 19.613         |
| J1537+1155 | 19.85                    | 48.34                    | 1.01           | 11.01436       |
| J1543+0929 | 17.81                    | 45.78                    | 5.9            | 35.24          |
| J1559+4438 | 334.64                   | 6.37                     | 2.3            | 56.1           |
| J1600-3054 | 344.09                   | 16.45                    | 2.4            | 52.3262        |
| J1614-2230 | 352.64                   | 20.19                    | 1.77           | 34.4866        |
| J1643-1224 | 5.67                     | 21.22                    | 0.42           | 62.4121        |
| J1713+0747 | 28.75                    | 25.22                    | 1.05           | 15.9915        |
| J1738+0333 | 27.72                    | 17.74                    | 1.97           | 34.778         |
| J1744-1134 | 14.79                    | 9.18                     | 0.42           | 4.13908        |
| J1866-3754 | 358.63                   | -17.21                   | 0.16           | 37.993         |
| J1853+1303 | 44.87                    | 5.57                     | 1.6            | 30.5701        |
| J1857+0943 | 42.29                    | 3.06                     | 0.9            | 14.3           |
| J1906-2000 | 10.34                    | -14.45                   | 0.7            | 37.993         |
| J1909-3744 | 359.73                   | -19.6                    | 1.26           | 10.3934        |
| J1932+0159 | 47.38                    | -3.88                    | 0.31           | 3.18           |
| J1935+1616 | 52.44                    | -2.09                    | 3.7            | 138.521        |
| J1939+2134 | 57.51                    | -0.29                    | 5.1            | 71.6398        |
| J2018-2839 | 68.1                     | -3.98                    | 0.98           | 14.172         |
| J2022-2854 | 68.86                    | -4.67                    | 2.1            | 24.64          |
| J2022+0154 | 87.86                    | 8.38                     | 1.8            | 22.648         |
| J2048-1016 | 30.51                    | -8.08                    | 0.95           | 11.456         |
| J2055+0630 | 79.13                    | -5.59                    | 3              | 97.313         |
| J2124-3558 | 10.93                    | -45.44                   | 0.3            | 4.601          |
| J2128-5721 | 338.01                   | -43.57                   | 0.4            | 31.853         |
| J2144-3933 | 2.79                     | -49.47                   | 0.16           | 3.35           |
| J2145-0550 | 14.78                    | -22.08                   | 0.57           | 17.807         |
| J2157+4017 | 90.49                    | -11.34                   | 2.9            | 70.857         |
| J2222-0137 | 62.02                    | -46.08                   | 0.27           | 3.27641        |
| J2313+4253 | 104.41                   | -16.42                   | 1.06           | 17.2758        |
### TABLE III. List of Large Magellanic Cloud and Small Magellanic Cloud pulsars

| Pulsar name       | Galactic longitude ($^\circ$) | Galactic latitude ($^\circ$) | Distance (kpc) | DM ($cm/pc^3$) |
|-------------------|-------------------------------|------------------------------|----------------|----------------|
| J0449-7031        | 282.29                        | -35.51                       | 53.7           | 65.83          |
| J0451-67          | 278.41                        | -35.29                       | 53.7           | 45             |
| J0455-6951        | 281.29                        | -35.19                       | 53.7           | 94.89          |
| J0456-7031        | 282.05                        | -34.97                       | 53.7           | 100.3          |
| J0502-6617        | 276.87                        | -35.3                        | 53.7           | 68.9           |
| J0519-6932        | 280.20                        | -33.25                       | 53.7           | 119.4          |
| J0522-6847        | 279.35                        | -33.17                       | 53.7           | 126.45         |
| J0529-6652        | 276.97                        | -32.76                       | 53.7           | 103.2          |
| J0532-6639        | 276.67                        | -32.48                       | 53.7           | 69.3           |
| J0534-6703        | 277.13                        | -32.28                       | 53.7           | 94.7           |
| J0535-6935        | 280.08                        | -31.94                       | 53.7           | 93.7           |
| J0537-6910        | 279.56                        | -31.74                       | 53.7           | –              |
| J0540-6919        | 279.72                        | -31.52                       | 53.7           | 146.5          |
| J0543-6851        | 279.13                        | -31.24                       | 53.7           | 131            |
| J0555-7056        | 281.46                        | -30.12                       | 53.7           | 73.4           |
| J0045-7042        | 303.65                        | -46.42                       | 62.4           | 70             |
| J0111-7131        | 300.67                        | -45.51                       | 62.4           | 76             |
| J0113-7220        | 300.62                        | -44.69                       | 62.4           | 125.49         |
| J0131-7310        | 298.94                        | -43.65                       | 62.4           | 205.2          |
| J0045-7319        | 303.51                        | -43.8                        | 62.4           | 105.4          |

### TABLE IV. Dispersion measure for LMC and SMC pulsars

| Pulsar name       | Experimental DM | MB  | NFW C=12 | NFW C=3 | FHG |
|-------------------|-----------------|-----|----------|---------|-----|
| J0449-7031        | 65.83           | 14.85| 381.1    | 123.4   | 20.0|
| J0451-67          | 45              | 14.7 | 366.7    | 120.0   | 19.7|
| J0455-6951        | 94.89           | 14.8 | 377.5    | 122.5   | 19.8|
| J0456-7031        | 100.3           | 14.8 | 380.4    | 123.2   | 19.9|
| J0502-6617        | 68.9            | 14.7 | 361.8    | 118.8   | 19.7|
| J0519-6932        | 119.4           | 14.8 | 374.7    | 121.9   | 19.8|
| J0522-6847        | 126.45          | 14.8 | 371.3    | 121.1   | 19.8|
| J0529-6652        | 103.2           | 14.7 | 362.8    | 119.1   | 19.7|
| J0532-6639        | 69.3            | 14.7 | 361.85   | 118.8   | 19.7|
| J0534-6703        | 94.7            | 14.7 | 363.5    | 119.2   | 19.7|
| J0535-6935        | 93.7            | 14.8 | 374.5    | 121.8   | 19.8|
| J0537-6910        | –               | 14.8 | 372.6    | 121.4   | 19.8|
| J0540-6919        | 146.5           | 14.8 | 373.3    | 121.5   | 19.8|
| J0543-6851        | 131             | 14.8 | 371.2    | 121.0   | 19.8|
| J0555-7056        | 73.4            | 14.8 | 380.65   | 123.3   | 19.9|
| J0045-7042        | 70              | 16.8 | 454.4    | 142.65  | 22.8|
| J0111-7131        | 76              | 16.7 | 444.8    | 140.5   | 22.7|
| J0113-7220        | 125.49          | 16.7 | 446.6    | 140.9   | 22.75|
| J0131-7310        | 205.2           | 16.7 | 442.0    | 139.9   | 22.7|
| J0045-7319        | 105.4           | 16.8 | 461.1    | 144.15  | 22.9|

### TABLE V. Model predictions for Andromeda galaxy DM

| MB  | NFW C=12 | NFW C=3 | FHG |
|-----|----------|---------|-----|
| 28.8| 282.5    | 114.6   | 37.3|