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DISTANCE MEASUREMENTS TOWARDS YOUNG MILKY WAY OBJECTS; ROTATION CURVE

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The paper discusses existing methods of distance determinations to bright objects inside our Galaxy. Possible inaccuracies are considered. Measurements of both: distances and radial velocities allow determination of the Milky Way rotation curve, believed to be flat because of the postulated Dark Matter halo around the Galaxy. We demonstrate the rotation curve, based on observations of CaII interstellar absorption lines in spectra of OB stars. Our high resolution spectra allow to measure both: distances and radial velocities with a high precision —free of the effects of stellar binarity and the line center uncertainties in rapid rotators. The resultant rotation curve of the Milky Way proves to be much more complex than either "flat" or "keplerian".

Keywords: Milky Way – rotation – interstellar medium

1. INTRODUCTION

The Galaxy, as well as other, similar objects, rotates. It's characteristic, spiral form is likely governed by the gravitation force and orbital speeds of galactic objects. Spiral galaxies are believed to contain not only the visible objects but also Dark Matter, distributed in the form of extensive halo. The presence of the latter should make the orbital speeds of the objects, external to our Sun, constant, independently of the distance to the galactic center. The function, presenting the orbital speed vs. galactic radii is called Rotation Curve. The latter is flat if the orbital speeds are constant, starting from a certain radius and keplerian —if the Dark Matter halo does not exist and the orbital velocities get systematically smaller with growing radii.

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Several years ago the presence of Dark Matter (DM) inside and/or around our Galaxy was questioned by Moni Bidin et al. (2012). Estimating the dynamical surface mass density at the solar position between Z = 1.5 and 4 kpc from the Galactic plane, the authors concluded that the local density of Dark Matter is at least an order of magnitude below the standard expectations, i.e. if the halo is present. However, Bovy & Tremaine (2012) used the model with different assumptions and concluded the accordance of observations to the Dark Matter existence paradigm. This fact makes all possible observational tests of the Dark Matter existence very important; the possibility that the same data applied in different models lead to contradictory conclusions proves clearly the insufficiency of necessary observations.

Let's assume that orbits of galactic objects are circular. Nearly flat rotation curves in outer parts of spiral galaxies were inferred by Sofue & Rubin (2001). This constant, independent on distance from the galactic center, velocity of galactic rotation is considered as a fundamental proof of the presence of the Dark Matter haloes. The Dark Matter should contain a vast majority of galactic masses. The existence of the Dark Matter in the Milky Way was questioned already by means of analyzing stellar motions (Kuijken & Gilmore (1989), Holmberg, & Flynn, (2000)). The above mentioned analyzes were based on motions of relatively nearby stars which gives a limited reliability to the results. The density of galactic objects declines quickly outside the solar orbit which makes constructing statistically significant samples of such objects difficult.

Significant differences between the determined rotation curves, as compared to the Keplerian ones, may shed more light on the problem of the Dark Matter also in or around our Galaxy. Maciel and Lago (2005) built the Galactic rotation curve based on a large sample of planetary nebulae and compared with that of Brand and Blitz (1993) which is based on HII regions. Rotation velocities of planetary nebulae (relatively old objects) are systematically lower than those for HII regions (very young objects).

The role of the observationally determined rotational curve of Galaxy is critical for proper modelling of the Milky Way. Since quite recently a big effort has been made to interpret observations of kinematics of interstellar gas, based on the assumption that HI, HII and H_2 clouds move on closed orbits, usually assumed to be circular. This may follow their mutual collisions as clouds collide much more likely than stars due to their big sizes. Collisions should "thermalize" the orbits making them circular. The above mentioned clouds are considered as tracers of the gas disc (thin disc). HII and H_2 objects are evidently spatially correlated since OB stars (used to measure HII clouds' distances) and exciting HII clouds, are recently formed out of dense, molecular interstellar clouds. The case of HI clouds, being revealed by the 21 cm spectral feature, remains uncertain.

The discrepancies of the galactic rotation curve from the Keplerian one are interpreted either in terms of the presence of Dark Matter or as a necessity of using the proposed MOND (Modified Newtonian Dynamics), see e.g. Milgrom (1983). Several years ago an argument for the flatness of the outer Galactic rotation curve was given by very precise astrometric measurements in the frame of the VERA program of trigonometric parallaxes and proper motions of a few star forming regions distributed far away beyond the solar orbit: Reid et al. (2009). These results favour a nearly flat, or even slightly rising outward Galactic rotation speed up to 13 kpc. However, the sample of objects, used in these studies, is extremely limited.

Sofue et al. (2009) have unified the existing data on rotation curves for our Galaxy into a single rotation curve by means of re-calculating distances and velocities, adopting for the galactocentric distance and the circular velocity of the Sun values ($R_{\odot}$,$V_{\odot}$)=(8.0 kpc, 200 km/s) respectively. His resulting curve is generally flat with two local minima or dips situated at radii 3 and 9 kpc from the Galactic center. The 3-kpc dip is consistent either with the bar or alternatively explained by a massive ring with the density maximum at a radius of 4-kpc. The 9-kpc dip is shown using different tracers and seems to be the most peculiar feature in the Galactic rotation curve. Sofue et al. (2009) explains it by a massive ring with the density peak at a radius of 11 kpc. This giant ring may be related to the Perseus arm. Evidently the sample of tracers observed outside the solar orbit (and believed to be the members of the Galaxy) is much smaller than those of insiders. Moreover, the scatter of individual determinations of distances and radial velocities grows in a stepwise manner outside the solar orbit (see the Fig.1 of Sofue et al. (2009)).

Galazutdinov et al. (2015) used high resolution spectra to determine intensities and radial velocities of 50 interstellar CaII sightlines, towards OB stars —members of the Milky Way thin disc. The method used allows to avoid problems with stellar binarity which creates doubts as to whether the observed radial velocity is that of the mass center. Moreover, stellar radial velocities must be determined using broad (Doppler broadening) or very broad (rotation) lines which makes measurements uncertain in a sharp contrast to very narrow interstellar lines. The rotation curve of Galazutdinov et al. (2015) is clearly keplerian; moreover, the already observed young clusters confirm the results based on CaII lines.

2. DISTANCES AND THEIR UNCERTAINTIES

The most traditional and basic method of determining distances to celestial objects is the trigonometric parallax. This is the only one fully independent and necessary to calibrate other methods.The method is very straightforward but also

—quite difficult in the case of determining large distances, necessary to investigate the Galactic structure. Very small angles can hardly be measured with high precision. This situation was supposed to be improved by the Gaia satellite (DR2). It seems to be of basic importance to check whether the Gaia DR2 distances are as correct as expected. Anyway —stellar binarity may cause some uncertainties, perhaps accompanied with some, undiscovered yet, factors.

The other, traditionally used method of distance measuring is that, using the photometric equation:

$$m - M = 5\log D - 5 + R - VE(B - V). \tag{1}$$

This simple equation is, however, full of traps. Absolute magnitude should be calibrated to spectral type and luminosity classes (using trigonometric parallaxes); thus M depends on the precision of the above calibration and of that of Sp/L estimate. The calibration is difficult since the sufficiently nearby OB stars (of precisely known trigonometric parallaxes) are very scarce. Moreover, if our target is a variable star, both m and M should be determined for the same phase. Such a situation seems very unlikely. The total–to–selective extinction ratio, R$-V$, varies from object to object (see Fitzpatrick & Massa 2007) but it's individual values are in many cases hard to be properly estimated. Moreover, E(B-V) depends once again on the proper spectral classification. Many sources of possible errors!

Another method, invented as long ago as in 1928 (Struve 1928) but developed for OB stars only quite recently (Megier et al. 2009) is based on intensities of interstellar CaII lines derived from high resolution spectra, i.e. on column densities of interstellar gas. This method requires also a calibration based on trigonometric parallax but this is the only calibration needed. Sets of trigonometric parallaxes from Hipparcos and Gaia allow such calibration. The method is not sensitive to Sp/L estimates as well as to stellar binarity or, more generally, variability. It's basic, purely empirical, equation is:

$$D_{CaII}[pc] = 77 + (2.78 + 2.60\frac{EW(K)}{EW(H)} - 0.932)EW(H). \tag{2}$$

The method works properly only if CaII lines do not show any saturation effects, i.e. when $EW(K)/EW(H) > 1.32$. Radial velocities of interstellar clouds can be measured precisely because the *Caii* lines are sharp. Moreover, clouds orbits are likely circular (thermalized) which facilitated determination of orbital speeds.

3. RESULTS

It is of basic importance to determine distances to the selected galactic objects. We used a long series of high resolution UVES (fed with the Kueyen VLT mirror) spectra from ESO to estimate distances using all three methods described in the Introduction, i.e. trigonometric parallaxes from Gaia DR2. spectrophotometric ones (our spectra have been used to check the existing Sp/L's) and the method based on column densities of CaII lines. A comparison between the results of all three methods can shed some light on the precision of the possible distances.

Fig. 1 presents the comparison of the distances based on Gaia DR2 trigonometric parallaxes and those, based on CaII column densities. The comparison shows that both methods give reasonably similar results until the distance of ∼2 kpc. For larger distances the scatter is unacceptably big.

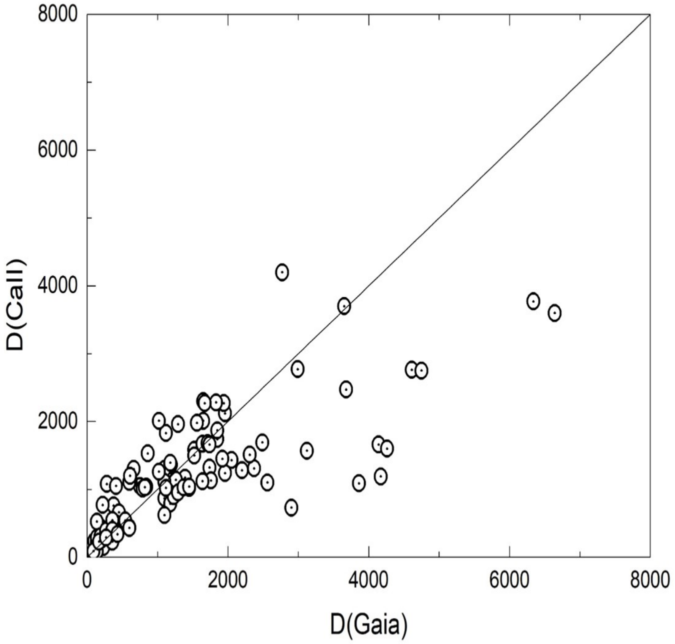

Fig. 1. A comparison of Gaia and CaII distances. Note the general agreement until 2 kpc.

The next figure (Fig. 2) compares the Sp/L distances to those of Gaia DR2. The result is quite astonishing. As in Fig. 1 the distances agree statistically until D∼2 kpc. Estimates of larger distances seem risky.

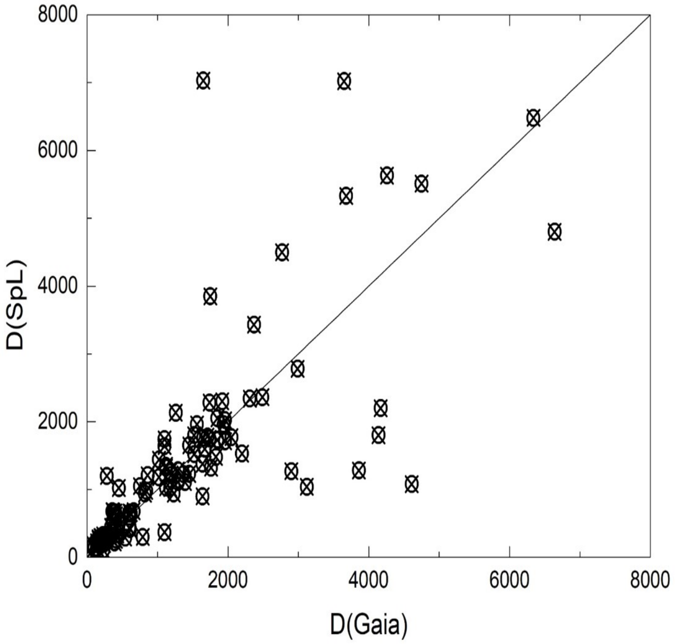

Fig. 2. A comparison of Gaia and Sp/L distances. Note the general agreement until 2 kpc.

It is thus not astonishing that while comparing CaII and Sp/L distances we get the same result.

Apparently distances to relatively nearby objects (up to 2 kpc) can be estimated quite reliably and thus the Milky Way rotation curve may be determined in the range of these 2 kpc. Larger distances are uncertain.

Galazutdinov et al. (2015) argued that the Milky Way rotation curve is rather keplerian than flat. However, they investigated only objects outside the solar orbit. What one can find inside the orbit of our daily star? We tried to investigate this using distances from both: Gaia parallaxes and from the Casc ii method. In both cases we used radial velocities of interstellar clouds. Going towards the galactic center we went a bit deeper than 2 kpc as the number of possible objects is relatively large in this direction. The result is astonishing (Fig. 4). The orbital speeds seem to get much lower when going inside the Milky Way disc. The result is the same, independently of the distance measuring method.

It seems that the orbital speeds of galactic objects are the highest at the solar distance! Both: inside and outside the solar orbit they seemingly get lower.

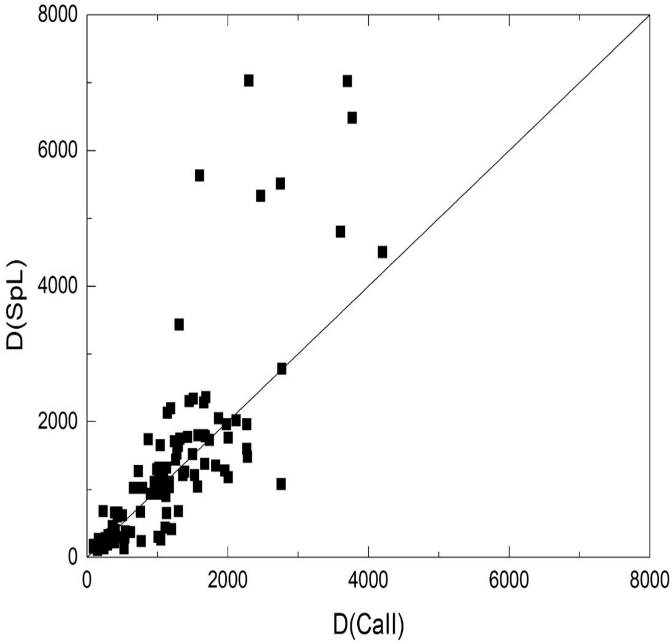

Fig. 3. A comparison of CaII and Sp/L distances. Note the general agreement until 2 kpc.

How the latter is related to the structure of the Milky Way disc? Currently it is impossible to answer this question.

4. DISCUSSION

Our considerations prove clearly that the problem of the galactic rotation curve —its shape and orbital speeds, remains open. We observe the thin disc of our Galaxy from the "frog" perspective and its general form is not accessible to our eyes. It is possible that the disk contains some streams of matter —possible results of galactic cannibalism. The orbital speeds seem to be relatively small inside the solar orbit but outside of it they seem to get smaller again. The latter may suggest a keplerian rather than flat rotation curve; however —how to interpret the curve inside the solar orbit? Apparently much more copious and precise data on distances and motions of bright, distant objects, are necessary to solve this problem.

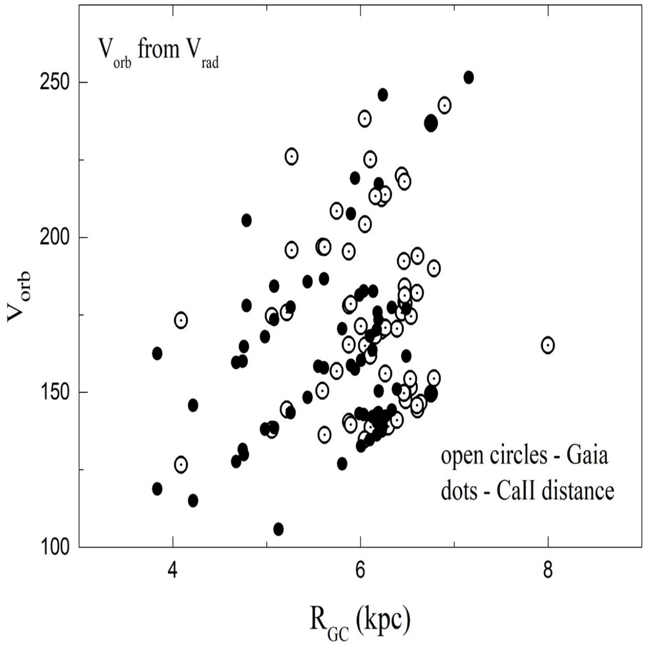

Fig. 4. Rotation curve of the Milky Way inside the solar orbit. Velocities are calculated for interstellar clouds. Distances are from both: Gaia and CaII method. The results are very similar.

5. ACKNOWLEDGEMENTS

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