How far is it? Distance measurements and their consequences

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Methods of measuring distances to objects in our Milky Way are briefly discussed. They generally base on three principles: of using a standard rod, of standard candle and of column density of interstellar matter. Weak and strong points of these methods are presented. The presence of gray extinction towards some objects is suggested which makes the most universal method of standard candle (spectroscopic parallax) very uncertain. Hard to say whether gray extinc-tion appears only in the form of circumstellar debris discs or is present also in the general interstellar medium. The application of the method of measuring column densities of interstellar gases suggests that the rotation curve of our Milky Way system is rather Keplerian than flat which creates doubts as to whether any Dark Matter halo is present around our Galaxy. It is emphasized that the most universal method, i.e. that of standard candle, used to estimate distances to cosmological objects, may suffer serious errors because of improper subtraction of extinction effects.

1 Introduction

The question: "How far is it?" in astronomy is very old. Ancient astronomers were able to estimate relative distances of planets: the longer is the orbital period (or – the smaller is the proper motion) the farther is the object. However, the stellar distances were a mystery. For Nicolaus Copernicus they were still attached to a sphere i.e. all situated at the same distance. How big? Copernicus concluded that "very big" because, if to situate horizontally a spy–hole, the opposite points are exactly in the horizon, i.e. they are separated by 180°. That means that our Earth size is negligible in comparison to that of "stellarum fixarum sphaera immobilis".

However, the Copernicus theory suggested a method of measuring stellar distances. If the Earth orbits the Sun then its positions in, say, January and in July should be reflected by different positions of stars. This phenomenon is known as "trigonometric parallax". Thus if one knows the size of the terrestrial orbit, he may measure distances to very distant objects, like stars. The idea was considered by another eminent astronomer – Tycho de Brahe. Using the similar method he was able to prove in 1577 that comets are astronomical, not atmospheric objects. He measured stellar positions with the precision higher than anybody else before and, moreover, calculated errors of his measurements. The latter were estimated as $\sim 50''$. Despite many efforts Tycho was not able to measure any trigonometric parallax. He knew very well that this result can be interpreted either as the lack of parallax (i.e. that the Earth is immobile) or that the existing parallax is smaller than the above mentioned $50''$. The second possibility frightened him so much (how huge and empty the Universe is!!!) that he started opposing the Copernicus theory, proposing (unsuccessfully) another model of the solar system (then – Universe).

Trigonometric parallaxes remained to be below the level of detection for a very long time. When the structure of the solar system was reasonably well known – let's remind that the orbit of Halley's comet was successfully calculated in the middle of XVIIIth century (Clairaut, Lepaute and Lalande) – the parallax was still out of the measurement possibilities. It was still, despite the fact that the orbital speed of the Earth was well known – in 1728 Bradley (the successor of Halley) measured the speed of light (c=301,000km/s) using the phenomenon of aberration. The precision of his measurement was so high that it was improved only by Foucault (c=299,796 km/s) in 1862. He must have known precisely the orbital speed of the Earth and so – the size of its orbit. Despite of this nobody was able to measure a single parallax and the question: "How far are stars?" remained unanswered.

The situation changed when F.W. Bessel (Bessel, 1838) measured the first stellar parallax – of 61 Cyg. As one could guess before, the parallax proved to be very small: 0."3136 ± 0."0202. It seems important that the dedicated satellite, Hipparcos, which measured trigonometric parallaxes in 1990–ties, estimated that of 61 Cyg as 0".286! Tribute to the old master!

The second half of XIXth century was in a big share devoted to measuring stellar parallaxes. They proved to be much smaller than those, which frightened so much Tycho de Brahe and allowed to raise the important physical questions concerning luminosities and masses of stars. Both these questions were raised little a bit after the measurement of the first parallax. However, the precision of ground–based measurements of angles is limited, theoretically to 0".01, but in practice reliable measurements are for parallaxes $\pi > 0''.04$. Thus the trigonometric parallax is inapplicable to distant objects beyond, roughly, 25 pc.

In 1863 the papal astronomer, father Angelo Secchi, started observational program comparing spectra of stars. After collecting about 4,000 spectra he was able to divide the observed objects into a few classes. Inside every of them the spectra seemed to be identical. This started spectral classification of stars, developed later by Annie J. Cannon and, finally by Morgan and Keenan. The spectral classification, together with estimates of absolute magnitudes (using trigonometric parallaxes) allowed Hertzprung and Russel to construct the famous diagram which for a century is the way of thinking for astrophysicists. The diagram and the two parameter spectral classification is based on the fundamental assumption that two stars of the same spectral and luminosity class (Sp/L) are identical i.e. are of the same masses, surface temperatures, internal structure and total luminosities (absolute stellar magnitudes).

The latter assumption offers another method of distance estimates. If a given **Sp/L** is one–to–one related to absolute magnitude $\mathbf{M_V}$ one can use the photometric equation:

$$m_V - M_V = 5logD - 5 \tag{1}$$

The above equation is based on the assumption that the stellar light is attenuated by the distance only, i.e. the larger is the distance the fainter is the observed star. The equation is extremely simple but... Many stars are, as we know, variables. Fig. 1 demonstrates the variations of Sp/L with time. To apply formula (1) one needs to acquire spectrum and photometric data at the same moment or, at least, at the same phase, otherwise the distance modulus (**m - M**) and, consequently – distance, will be incorrect.

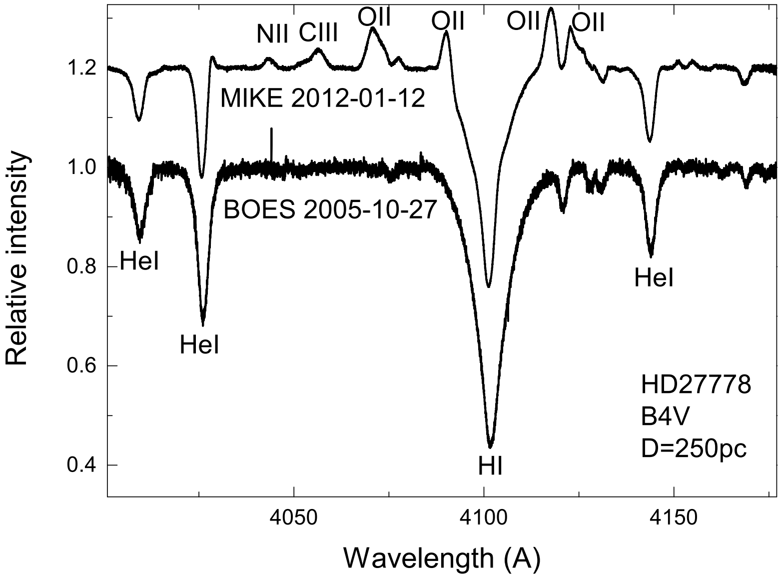

Fig. 1: Two spectra of the same star in two different epochs; it's evident the Sp/L is variable.

However, it is not the end of problems with the spectroscopic parallax. The space between stars is not empty but filled with a very diffuse medium, discovered as late as in XXth century. The history started from the detection of two apparently non-stellar **H** and **K** lines of the ionized (that time named "detached") calcium ((Hartmann, 1904)). The lines have been found as "stationary", i.e. not sharing variations of radial velocities of stellar lines in the spectrum of the binary δOri. Some atomic gas, forming absorption lines in interstellar clouds (the lines were quickly shown as Doppler splitted) cannot, however, influence distance measurements.

Trumpler (Trumpler, 1930) proved that the starlight is additionally attenuated by interstellar extinction, caused by dust particles. Trumpler proposed that the extinction may be caused by tiny grains which leads to selective extinction and by larger "meteoritic" bodies which may cause neutral (gray) extinction. This kind of extinction may be caused by dust grains of sizes exceeding wavelength of visible light. This requires to rewrite the equation (1) into the more general form:

$$m_V - M_V = 5logD - 5 + A_V \tag{2}$$

which establishes the connection between the apparent magnitude – $\mathbf{m}_V$, the absolute magnitude – $\mathbf{M}_V$, the distance – **D**, and the interstellar extinction – $\mathbf{A}_V$. The extinction term $\mathbf{A}_V$ is usually replaced by $\mathbf{R}_V$***E(B-V)** where $\mathbf{R}_V$ is called the total-to selective extinction ratio. Moreover, it may be necessary to add a constant term to the extinction – the term which does not depend on wavelength,

$$m_V - M_V = 5logD - 5 + R_V * E(B - V) + C \tag{3}$$

C, which is the gray extinction term, proposed by Trumpler. It is both – very difficult to prove either the existence or lack of non–zero gray extinction term. The latter acts in the above equation exactly like distance, i.e. attenuates light at all wavelengths in the same fashion. Let's add that extinction effects are totally absent in all stars for which ground–based trigonometric parallax is available. They are usually observed in bright, young, OB stars, which are generally very scarce; the latter phenomenon makes very difficult the calibration $\mathbf{Sp/L} \rightarrow \mathbf{M_V}$ for these objects.

Apparently extinction causes serious troubles to those, who try to estimate distances using the "standard candle" method, i.e. taking absolute magnitudes from a calibration $\mathbf{Sp/L} \rightarrow \mathbf{M_V}$ and trying to get rid of the extinction effects. The extinction law (curve) varies from cloud to cloud – see e.g. Fitzpatrick & Massa (Fitzpatrick & Massa, 2007). The paper shows large differences in the extinction curve shapes and also in the total–to–selective extinction value. Thus color excess does not characterize fully the interstellar extinction along any chosen sightline. Moreover, color excess says nothing about the possible gray extinction.

Is it possible to avoid the above mentioned problems? It seems possible to a certain extent, i.e. for objects concentrated in the Milky Way thin disc. The method was proposed by Struve (Struve, 1928) who assumed that column densities of interstellar atoms may be proportional to lengths of sightlines. In particular the column density of CaII, calculated from the intensities of H and K lines, may be very useful for this purpose. However, the method is limited to very hot stars; for objects later than B3 stellar components prevent observers from proper estimates of column densities. Moreover, only for a few such stars one can measure trigonometric parallaxes using ground based apparatus and thus direct calibration of the proposed method was not possible for a long time.

The situation has changed when the mission of the Hipparcos satellite was completed. Its parallaxes were roughly an order of magnitude more precise than the ground based ones. Thus the precise trigonometric parallaxes became available up to the distance of 250 pc which contains many OB stars (only a few of them can be measured using ground–based instruments). We have collected the set of 290 high resolution echelle spectra of OB stars in the thin galactic disc. The results are presented by Megier et al. (Megier et al., 2009). Distances to OB stars may be estimated using the empirical equation:

$$D(CaII) = 77 + (2.78 + 2.60/EW(K)/EW(H) - 0.932)EW(H) \qquad (4)$$

where EW's are equivalent widths of the CaII lines and can be applied if the ratio EW(K)/EW(H)>1.32. It is interesting that only a few objects do not fulfill the above condition. Apparently the galactic disc is evenly filled with tiny, optically thin clouds, which are revealed by unsaturated Doppler components of CaII.

As mentioned above the spectroscopic distances may be incorrect because of:

- errors of the $\mathbf{Sp/L} \rightarrow M_V$ calibration
- stellar variability leading to a misfit of **Sp/L** based M_V's and colors and photometric measurements
- improper estimates of the total–to–selective extinction ratio
- unknown influence of the possible gray extinction

and the resultant errors may be quite large. On the other hand the interstellar spectral features do not change with time (Fig. 2).

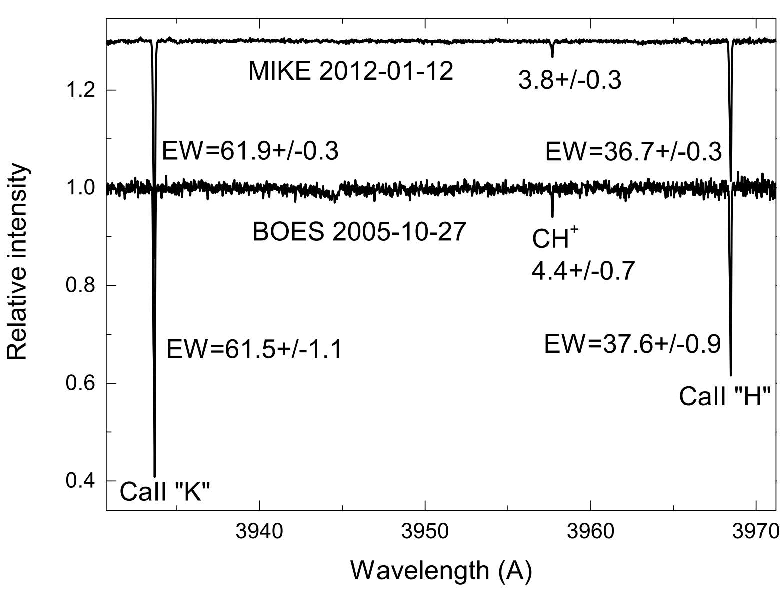

Fig. 2: The same two spectra as in the previous figure. Interstellar features do not show any variability. Their EW's are given in the plot.

The lack of variability of interstellar features makes them more reliable distance indicators than stellar magnitudes. Moreover, the CaII method depends only on one calibration which leads to the formula 4. Naturally it would be better to have the calibration based on a bigger sample of objects and the sample of spectra of higher resolution and signal to noise ratio but anyway the method seems currently to be the most reliable one inside the Milky Way thin disc.

2 GAIA distance measurements

The new satellite, dedicated to parallax measurements, GAIA, is currently at the orbit. The first data release took place at September 14th 2016. Among the stars to which distances can be estimated using the above mentioned data there are about $\sim$ 130 OB stars which the sample allows to compare different methods of distance determinations. The result of such comparison is shown in the Fig. 3.

It is evident that the distances, determined either using the direct GAIA measurements of trigonometric parallaxes and those, following the CaII lines' intensities are in general agreement though a very substantial scatter is observed. However, the scatter is symmetrical, relating to the identity line. Apparently the scatter does not follow only errors in the CaII method but in both. Some of the direct GAIA measurements are evidently erroneous. In the IC2944 aggregate stars, belonging beyond a doubt to it (proper motions plus radial velocities), distances vary in GAIA data from 1000 pc to 12500 pc! At the same time the CaII based distances vary between 1310 and 1760 pc. Thus to make sure that any individual distance is correct it is reasonable to

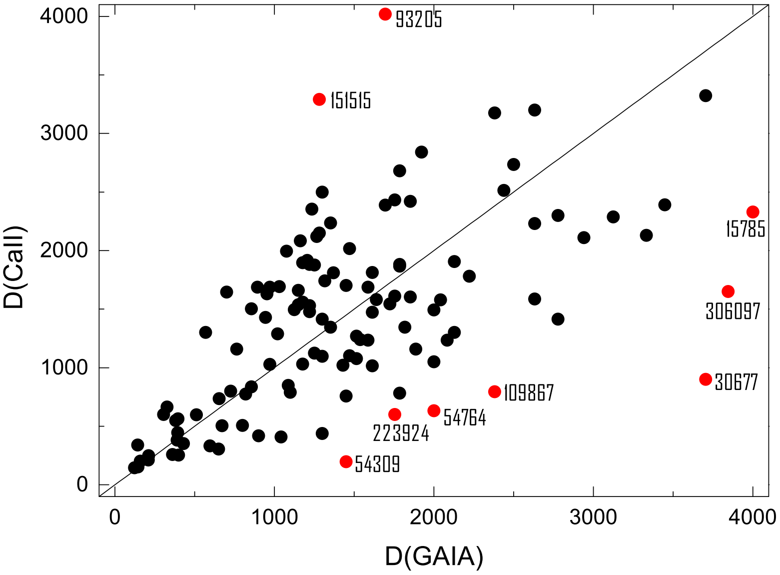

Fig. 3: The comparison of GAIA distances with those, based on Ca II lines. The line illustrates the postulated identity. The distances are in general the same, but the scatter is substantial. The outliers are marked.

estimate it using more than one method.

3 Evidencing gray extinction

Ori OB1 association, centered at the Orion Trapezium, is certainly one of the well known young stellar aggregates where star forming processes are still active. The distance to this cluster was first estimated by Trumpler (Trumpler, 1931) as 540pc. He also estimated the size of nebula as 8 pc. Trapezium is thus out of the range of typical, ground based parallax measurements. Hipparcos parallaxes for the Trapezium stars are negative and thus – useless. However, quite recently, Menten et al. (Menten et al., 2007) measured the trigonometric distance to the Trapezium, using VLBI. The distance is 414 ± 7 pc.

Recently I collected the spectra of two Trapezium stars: HD37022 and HD37020 using the high precision HARPS-N spectrograph, fed with the 3.6m Telescopio Nazionale Galileo. The spectra are very similar, leading to the same spectral type and luminosity class of both objects.

Fig. 4 proves evidently that the two stars must be nearly identical, in particular of the same absolute magnitude. Their distances, estimated using the Ca II lines, are 411 pc for HD37022 and 422 pc for HD37020 i.e. the average is 416 pc while that of Menten et al. – 414. However, the spectrophotometric distances of HD 37022 and HD37020 are: 419 and 905 pc respectively, using the individual total–to–selective extinction ratios from Fitzpatrick & Massa (2007). Considering the extraordinarily large spectrophotometric distance to HD37020 one can point:

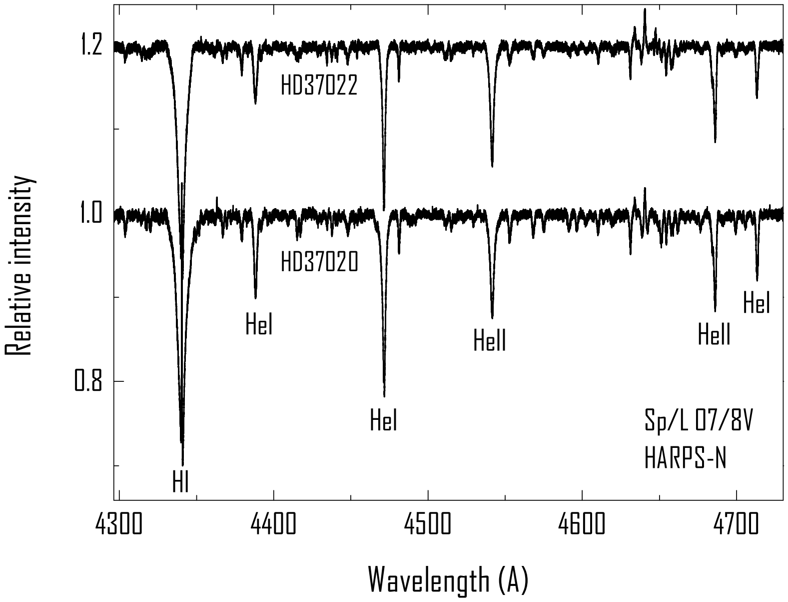

Fig. 4: Identical spectra of two Orion Trapezium stars, apparently of the same Sp/L.

- both stars are of the same **Sp/L** and so → of the same $\mathbf{M_V}$
- the B-V colors of both objects are identical (0.03) and so – the color excesses (0.32)
- the $\mathbf{R_V}$ values are atypical but calculated independently for both objects by Fitzpatrick and Massa (2007) and lead to almost identical color extinctions

The large difference in the apparent magnitudes is thus not an effect of different Sp/L, not of different colors and not of different R_V's. The only factor which may cause the observed difference (formula 3) is thus the gray extinction ((Krełowski et al., 2016b)).

Let's consider another similar case. This is HD66811 (ζPup) – one of the brightest and hottest stars (V=2.25; Sp/L=O4If). In this case D(trig) = 330 pc, D(CaII) = 265 pc and D(Sp/L) = 637 pc. The first two measurements are fully accordant while the third one is unacceptably large. As before, the first guess may be an improper spectral classification. This is, however, not possible since the star is the O4If standard according to Walborn & Fitzpatrick (Walborn & Fitzpatrick, 1990). It is important to mention that HD66811 is unreddened; its E(B-V) is 0.01, i.e. in the range of photometric error. Thus: Sp/L is certain and color extinction does not exist. The only possibility is that the distance excess, evident in the spectrophotometric method, is caused by some gray extinction.

The spectrum of HD66811 is compared in Fig. 5 to that of HD92964. The latter object is at almost the same distance but the Doppler structure of H and K lines in both spectra is quite different. In the former we clearly see at least three Doppler components while in the latter only a single component is seen. However, the column

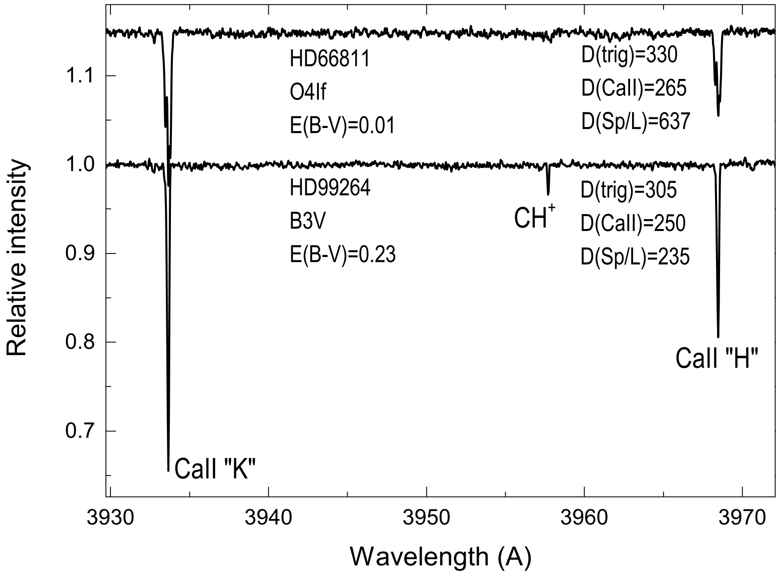

Fig. 5: Interstellar CaII lines in the spectrum of HD66811 compared to HD92964. Despite these, only TiII and NaI interstellar lines are seen in the spectrum of HD66811. In the reddened object, HD92964, also the molecular CH^+ feature is seen.

densities are similar, leading to similar CaII distances of both stars being reasonably accordant with the Hipparcos trigonometric measurements. In the case of HD92964 the above distances are also similar to that derived from the Sp/L method. In the latter object, which is reddened, one can trace also the molecular CH^+ line being absent in HD66811. Apparently molecular features (and diffuse bands) are related to reddening rather than to the total extinction and the strongest interstellar lines. Perhaps molecules are formed using surfaces of rather small grains as the formation sites; larger grains do not catalyze chemical reactions as their temperatures do not depend strongly on absorptions of single photons.

It seems of importance to mention that while comparing trigonometric with spectrophotometric distances, several points, representing the latter, show a substantial distance excess, which may be caused by the gray extinction. The same trigonometric distances, compared to the CaII ones, show only some scatter around the identity line (for both: Hipparcos and GAIA); no systematic effects are observed. For large distances, where trigonometric parallaxes are not available, also several spectrophotometric distances are excessively large in comparison to CaII ones ((Krełowski et al., 2016a)). Thus the effects of gray extinction may be reasonably popular among early type stars.

Let's summarize: every method of distance determination has some limitations

- Trigonometric parallax is limited to relatively nearby stars (the extension by GAIA did not change the general situation); parallaxes of multiple stars are often flawed

- Spectroscopic parallax (the most universal method) requires calibrations of $\mathbf{M_V}$ for **Sp/L**, simultaneous spectral and photometric observations and individual extinction law; gray extinction remains a puzzle
- CaII method works properly only in the Milky Way disc but is based on one calibration only and is accordant with GAIA up to 4000 pc
- it is important to compare measured distances of every object acquired, using more than one method.

The above arguments clearly prove that the best method of determining distances in the galactic disc is the CaII one. The method is not sensitive to improper spectral classification, misfits of variability phases between spectral and photometric data, improper estimates of interstellar extinction, to multiplicity of targets and depends on one calibration only. Moreover, the calibration proved to be valid also at large distances, available to GAIA, but the latter are sometimes seriously flawed, likely due to multiplicity of many stars.

There is one specific question: are the gray extinction effects originated in the general interstellar medium or in circumstellar debris discs only? It is easily seen that some of newly born stars are seen through their circumstellar discs, most likely protoplanetary ones. It is reasonable that in such discs dust particles stick one to one, forming larger grains (up to planets). The first step of such the disc evolution may be formation of relatively large grains, of the size exceeding wavelengths of visible light, causing gray extinction. Let's remind that the effects are seen only in spectra of rapidly evolving, young stars. However, currently one cannot bring any evidence that similarly large dust grains cannot be present in the general interstellar medium.

4 The Milky Way structure

Having a correct method of distance estimates is of basic importance while investigating the structure of the Milky Way. Our Galaxy evidently rotates and the observed bright clouds, from which it took the name, are close to its equator. If our Galaxy is similar to other spiral ones, the majority of the diffuse matter should be concentrated also close to the equator being at the same time the raw material for new generations of stars, in particular for young population of rapidly evolving OB stars. The distribution of the latter in the Milky Way and their motions determine thus the galactic rotation (they are the best tracers of it).

The orbital speed of rotation may decline with the distance from the galactic center (if the Galaxy rotates according to Kepler's laws) or be constant starting from certain radius (flat rotation curve). The latter may be true if the visible Galaxy is encircled with a halo of the so–called "dark matter" i.e. the form of matter which does not interact in any way with electromagnetic radiation.

The existence of Dark Matter around spiral galaxies (like our own Milky Way) is indirectly, dynamically indicated by the nearly flat rotation curves in the outer parts of these galaxies that are constructed under the assumption of circular rotation of the tracers (e.g. OB stars) – see e.g. Sofue & Rubin (Sofue & Rubin, 2001). This approximately constant speed of galactic rotation, independent of the distance from the galactic centers, is usually considered as the evidence of the presence of Dark Matter around our and other galaxies. However, the existence of Dark Matter in the Milky Way has been questioned by analyzing stellar motions (Kuijken & Gilmore, 1989; Holmberg & Flynn, 2000; Moni Bidin et al., 2012). These analyzes were based

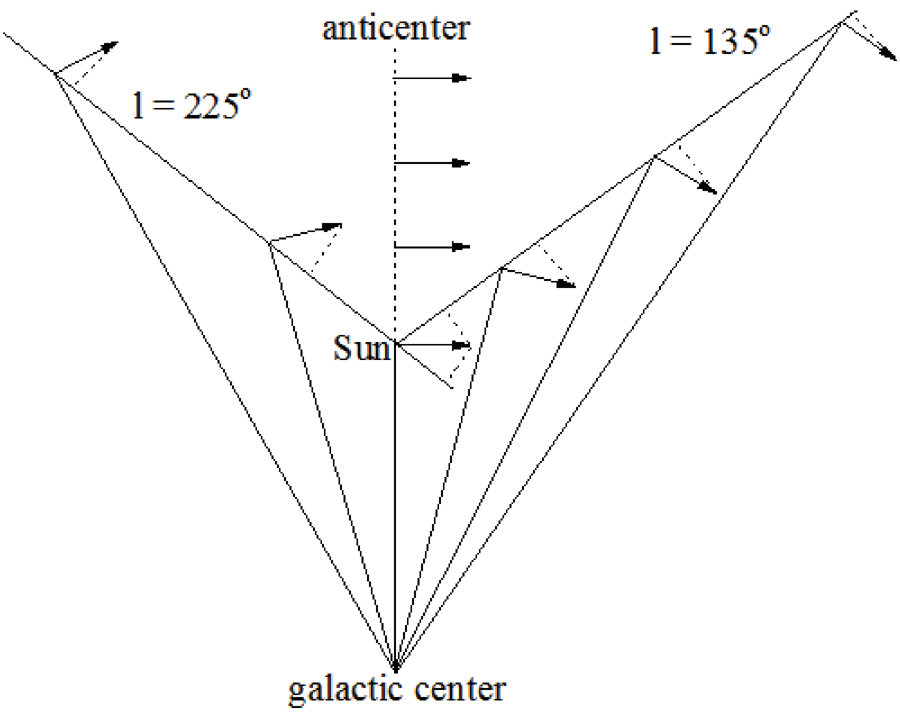

Fig. 6: Schematic sketch of the radial velocities following the galactic disc rotation.

on the motions of quite nearby stars. This is because the density of galactic objects declines outside the solar orbit, making it difficult to construct statistically significant samples of tracers situated outside the solar circle (where the rotation curve should be really flat if the dark halo exists).

An analysis of the CaII profiles allows to estimate both distances and radial velocities of the clouds situated in a close vicinity of the observed stars. The best direction to check the form of rotation curve of our Galaxy is the galactic longitude $l = 135°$ where the individual Doppler components should be most evidently separated (Fig. 6).

The growth of blue shift of more and more distant clouds along the $l = 135°$ direction in the Milky Way disc is evident; however, the growth is different for keplerian and flat rotation curves. The sketch demonstrates also that the radial velocities towards the galactic anticenter should be close to zero. Both theoretical curves are compared to the observational data in Fig. 7.

It is quite evident that the rotation curve of our Galaxy is rather keplerian than flat and thus the postulated dark halo around it seems very doubtful (for details see Galazutdinov et al. (Galazutdinov et al., 2015)). The plot presents radial not orbital velocities because it is more evident if demonstrating simple measurements. Error bars are not added but the distance uncertainties do not change the result (those

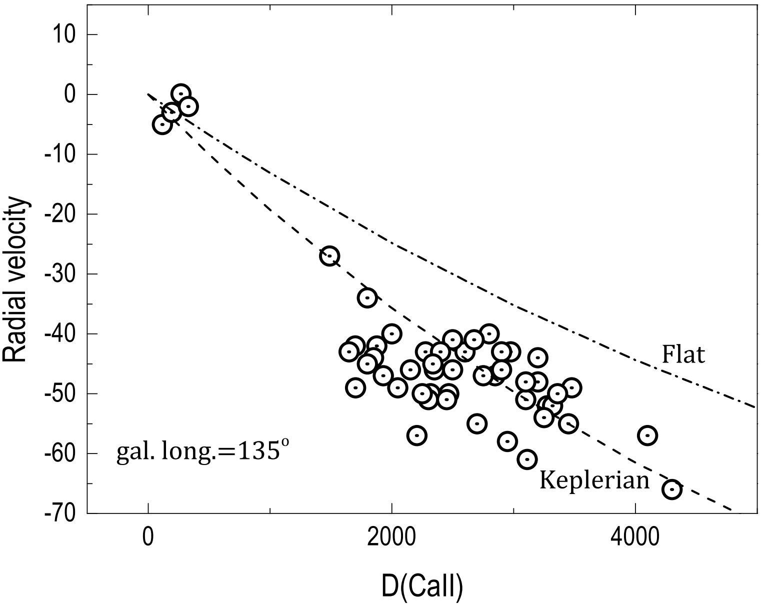

Fig. 7: Schematic theoretical rotation curves of the Milky Way (keplerian and flat) and the observational points.

of radial velocities are negligible for sharp interstellar lines). It is also important that radial velocities of clouds, seen in the anticenter direction, show radial velocities being just radial components of the intrinsic solar motion towards the apex, i.e. about 13 km/s.

5 Intergalactic extinction?

One step further we may have to deal with intergalactic matter and possible extinction caused by this material. Such the matter evidently exists and exists in the form of neutral hydrogen clouds. This conclusion follows the observations of severely Doppler–shifted Lyman lines (Lyman Forest). The lines, originated in the far–UV, are observed in the visible range because of the cosmological red–shift. Apparently, along a sight–line to any cosmological object, one can see hundreds of Doppler components of atomic lines, revealing HI clouds. Are these clouds filled with dust grains which may cause intergalactic extinction? It is extremely difficult to answer this question as none of such clouds can be observed separately. At first we do not know how intrinsic spectra of distant galaxies or quasars should look like (Sp/L $\rightarrow M_V$). Moreover, the extinction of any single cloud should be very small but we see the sum of the effects of many clouds, i.e. some ill–defined average. Anyway – let's try to guess what a result of such extinction could be?

Let's assume that every intergalactic cloud produces a very little of extinction which obeys the same law as our Milky Way average (Krelowski & Papaj, 1992). The more distant is every cloud – the more distracted is the extinction curve because of

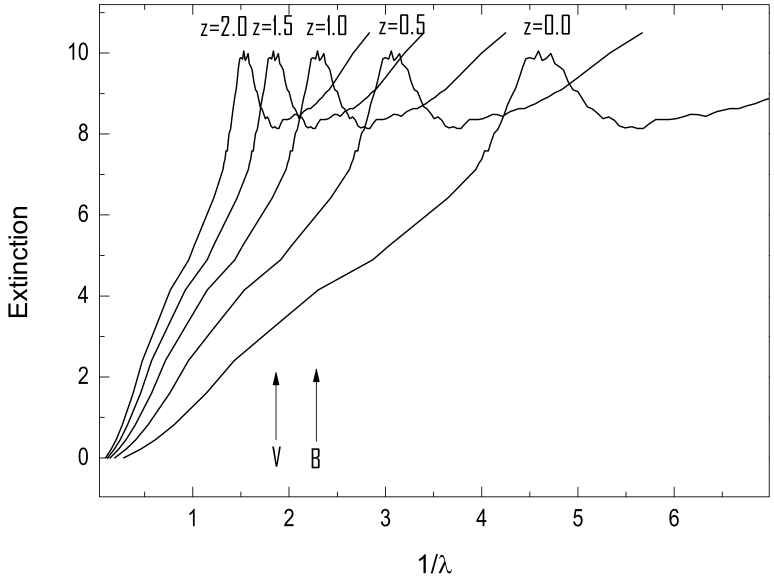

Fig. 8: Galactic extinction curves distracted by the cosmological redshift.

the cosmological red–shift which alters the form of extinction curve. In our Galaxy the extinction grows with the reciprocal wavelength with one maximum near 2200 Å; the cosmological red–shift moves the UV part of extinction curve towards the visible range. When $z = 1$ the extinction maximum (2200 Å) moves to the B band (4400 Å). This means that the extinction in this band will be higher than "normal"(in relation to E(B-V)) because of the "Lyman forest" effect. Higher extinction leads to distance excess. The latter can be interpreted in terms of "dark energy" because the distant galaxies and quasars seem to be farther than they are in fact (and farther than the Hubble's law, calibrated using relatively nearby objects, where the extinction bump is still in far–UV, predicts).

Let's emphasize that when $z \sim 1$ the extinction maximum reaches the B band and thus the extinction in this range becomes larger in comparison to possible E(B-V), substantially larger. Moreover, the "2200 bump forest" can easily create enhanced extinction which is nearly gray because the individual, red–shifted bumps, form a kind of continuum (Fig. 8). Apparently the idea of cosmologically modified intergalactic extinction allows to interpret the effects which otherwise lead to the idea of "dark energy". Both hypotheses are out of the possibility of detections/measurements (one must not investigate any single intergalactic cloud as well as to detect "dark energy"). Only the extinction hypothesis is less exotic.

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