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Hunting for invisible dust in the Milky Way☆

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ABSTRACT

Methods of measuring distances to distant objects, allowing to investigate structure of our Milky Way, are briefly discussed. The methods may be based on three principles: using standard rod, standard candle and column density of interstellar matter. Using of the first one is generally restricted to pretty nearby objects. The third one can be applied in the thin galactic disc only. The spectrophotometric method (standard candle) is the most universal one but it involves uncertainties related to calibration the “standard candle” parameters and the interstellar extinction effects. Weak and strong points of these three methods are presented. The presence of gray extinction towards some objects is suggested which makes the most universal method of standard candle very uncertain. It's difficult to say whether this extinction appears in the form of circumstellar debris discs or is present 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 to whether any Dark Matter is present in 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

Since many centuries astronomers ask one basic question: how far are celestial bodies? Nicolaus Copernicus said: “very far”, because he found two opposite limits of horizon, seen through a spy-hole, separated by 180° which led to the conclusion that the Earth size is negligible in comparison with “stellarum fixarum sphaera immobilis”. However, his theory resulted with the conclusion that, since the Earth orbits the Sun, stars seen at some moment and 6 months later should be found moved in relation to the celestial sphere. This phenomenon is known as “trigonometric parallax”. Another eminent astronomer, Tycho Brahe, tried to find the parallax but he failed. Tycho was the first astronomer who estimated errors of his measurements and found that his positions of stars are accurate up to 50″. The lack of observable parallax may be the result of the lack of the phenomenon itself or the parallax may have existed but being smaller than the above mentioned 50″. Tycho was really frightened by the enormous empty space around us (if the second idea is true) and thus tried to create a Universe model in opposition to that of Copernicus, i.e. with the stationary Earth. Parallax was not observed by centuries despite the fact that in XVIII century the structure of the solar system was known with the precision allowing to calculate the orbit of the Halley's comet (Clairaut, Lepaute and Lalande) and estimate the speed of light using the phenomenon of aberration (Bradley). Also in the middle of XVIII century transits of Venus on the solar disc were observed (following the idea of Halley – how to measure precisely the astronomical unit) but no stellar parallax was measured. The first successful measurement of parallax, of the star 61 Cyg, was done by Bessel (1838). He estimated the parallax of the star as 0″.3136 ± 0″.0202. The current value, measured using the dedicated satellite, Hipparcos, is 0″.286.

It was immediately obvious that the stellar distances are very large, much larger than those which frightened Tycho. Parallaxes of many of them may be too small to be measured at all. However, in XIX century the papal astronomer, Angelo Secchi, started to compare stellar spectra. From 1863 on, he divided the observed stars into several categories; inside every one the spectra (strength ratios of absorption lines) were very similar. The conclusion was that one can find several groups of stars being practically identical inside every set. This idea was developed later, in particular by Annie Jump Cannon, born in 1863. She constructed the Harvard spectral classification, developed later to the Morgan - Keenan, two parameter system. In the latter every star being of the same Sp/L (spectrum and luminosity class) should be characterized by the same absolute magnitude, i.e. to emit the same amount of energy, distributed in the same way in the spectrum. The spectral classification allows thus to estimate “spectroscopic parallax” i.e. the distance to any observed star of the known Sp/L, which leads to the photometric equation:

☆ Based on spectra from Las Campanas MIKE, TNG/HARPS–N and ESO Feros spectrographs.This is the printed version of the talk presented during the 9th meeting on Cosmic Dust hold in Sendai, Japan, August 2016.

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$$m_V - M_V = 5logD - 5 \quad (1)$$

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 of a given spectrum and luminosity class. The equation is very simple but many stars are, as we know, variable. If so a stellar spectrum may be variable and the Sp/L (and, consequently – M_V) is phase–related. Thus both: apparent and absolute magnitudes should be determined at the same phase of variability which is practically never done.

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. Trumpler (1930) proved that the starlight is additionally attenuated by interstellar extinction, caused by dust particles. The interstellar extinction of starlight is the most indicative phenomenon revealing the presence of dark clouds of diffuse matter in the Galaxy. The extinction is the sum of two physical processes: **absorption** and **scattering**. The presence of extinction forces us to rewrite the Eq. (1) in the form, proposed by Trumpler:

$$m_V - M_V = 5logD - 5 + R_V * E(B - V) + C \quad (2)$$

where $\mathbf{m}_V$ is the apparent magnitude, $\mathbf{M}_V$ – the absolute magnitude, **D** – the distance and R_V***E(B-V)** and **C** – color and gray extinction terms. **E(B-V)** is the color excess, i.e. the difference between the observed color **(B-V)** and its intrinsic (for a given **Sp/L**) value, (e.g. Papaj et al., 1993). 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 in all wavelengths in the same way. It was proposed in 1930 by Trumpler, but its presence remained doubtful until now.

There is a little doubt if any that the interstellar extinction is caused by dust particles. However, properties of solid state matter are much more difficult to be determined spectroscopically than those of matter in gas state. Moreover, one can observe only a very limited amount of features originated in interstellar dust. Generally the available observational data concerning the interstellar dust are limited to:

- extinction curve which is a graphic version of the extinction law; in general the extinction grows towards blue – only one maximum is observed near 2200 Å – followed by a minimum near 1800 Å. It is believed that one population of grains cannot account for the whole extinction curve: the visual/infrared segment must be caused by relatively large grains which may be only a source of gray extinction in ultraviolet. Thus the 2200 Å bump is usually related to small graphite grains while the final far–UV rise – to small silicate grains or to polycyclic aromatic hydrocarbons (PAHs)
- total–to–selective extinction ratio $\mathbf{R}_\mathbf{V}$, i.e. the factor necessary to “translate”the extinction curve to absolute extinction values and to deredden a target in practice
- elemental depletions in the interstellar gas. It is well–known since 1974 (Field, 1974) that abundances of many heavy elements in the interstellar gas are severely below “cosmic abundance” the only “sink” for these elements may be the interstellar dust. An analysis of the depletions may help to determine chemical composition of the dust particles.

As recently emphasized by Fitzpatrick and Massa (2007), the far–UV segment of extinction curve is very sensitive to Sp/L uncertainties. In the above mentioned survey low far–UV extinction is usually accompanied with a high value of total–to–selective extinction ratio $\mathbf{R}_\mathbf{V}$; the latter may vary between 2.0 and 6.5. It seems well-established that extinction curves may differ from object to object. The evident deviations from the galactic average extinction curve are scarce; perhaps because in a vast majority of cases one observes reddened stars through several clouds being intersected by a sightline. This process leads to averaging optical properties of individual clouds to the same mean extinction curve.

Apparently extinction causes serious troubles to those, who try to estimate distances using the “standard candle” (spectroscopic parallax) method, i.e. taking absolute magnitudes from a calibration of the latter to **Sp/L** and trying to get rid of the extinction effects using average extinction curve and $\mathbf{R}_\mathbf{V}$.

Is it possible to avoid the above mentioned problems? It seems possible to a certain extend, i.e. for objects concentrated in the Milky Way thin disc. The method was proposed by 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, discovered as stationary by Hartmann (1904), 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 until recently.

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 (parallaxes of 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. (2009). Distances to OB stars may be estimated using the empirical equation:

$$D(CaII) = 77 + (2.78 + 2.60/EW(K)/EW(H) - 0.932)EW(H) \quad (3)$$

where EW(K) and EW(H) are equivalent widths of both CaII lines. Formula (3) 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. Their sum remains unsaturated as well.

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

- errors of the M_V vs. Sp/L calibration
- stellar variability (or binarity) leading to a misfit of $Sp/L \to M_V$ and photometric measurements
- improper estimates of the total–to–selective extinction ratio R_V
- 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. 1) and the method of distance determination from CaI lines needs only one calibration.

The lack of variability of interstellar features makes them more reliable distance indicators than stellar magnitudes. Moreover, the CaI method depends only on one calibration which leads to the formula (3). 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 the most reliable one inside the Milky Way thin disc.

2. Searching for gray extinction

Let's consider a very interesting case of the Orion Trapezium. The aggregate is considered as the most nearby one where star formation processes are now active. Recently we have collected high resolution and high S/N ratio spectra of the two stars: HD37022 and HD37020. The spectra are from HARPS-N spectrograph attached to the 3.58 m Telescopio Nazionale Galileo. The resolution is R = 115,000. They do allow precise comparison of both stars spectra.