PROCEEDINGS OF SCIENCE

Determination of Distances to Galaxies by the Brightest Stars

N. A. Tikhonov,[a,*] O. A. Galazutdinova[a] and G. M. Karataeva[b]

[a] *Special Astrophisical Observatory RAS, Nizhnij Arkhyz, Karachai-Cherkessian Republic, Russia 369167*

[b] *St. Petersburg University, St. Petersburg, 199034 Russia*

E-mail: ntik@sao.ru

Currently, the common TRGB method (Tip of Red Giant Branch) for determining the distances to galaxies along the upper boundary of the red giant branch has a measurement limit of approximately 25 Mpc. In more distant galaxies, red giants are not visible in the images of the Hubble Space Telescope (HST). For such galaxies, we propose to use the already well-known method of the brightest stars, calibrated by us on the basis of HST telescope images for 150 galaxies of different types and luminosities. The obtained relationship between the luminosities of galaxies and their brightest stars can be used for irregular and spiral galaxies in a large span of their luminosities ranging from $M_B = -8^{\mathrm{m}}$ to $M_B = -19^{\mathrm{m}}$. Because the brightest stars have a luminosity 4–5 magnitudes higher than the luminosity of red giants, the method of the brightest stars can be applied for significantly more distant galaxies. The accuracy of the brightest blue star method is $0\overset{\mathrm{m}}{.}4$.

The Multifaceted Universe: Theory and Observations - 2022 (MUTO2022)
23-27 May 2022
SAO RAS, Nizhny Arkhyz, Russia

*Speaker

PoS(MUTO2022)021

1. Introduction

Measuring distances to space objects allows one to determine their physical parameters: dimensions, luminosities and spatial structure. This means that the scale of cosmic distances refers to the primary fundamental parameters. Currently, there are dozens of methods for distance determination, but for galaxies only five of them are most often used: the Tully–Fisher relation, supernovae SNIa luminosities, period-luminosity relation for Cepheids, Hubble constant (H_0) and the TRGB method. Other methods are used much less frequently.

The most accurate and frequently used TRGB method proposed by Lee et al. [1] has an accuracy of $0.^{m}1$. Jaung and Lee [2] improved the accuracy of the method to $0.^{m}06$. The method is actively used but it is applicable to galaxies located no further than 25 Mpc. The limitation arises due to the photometric limit of the HST images.

Figure 1 shows an image of the center of the galaxy NGC 4038 obtained with the HST telescope.

The Hertzsprung–Russell diagram for all the stars in this galaxy is shown in Fig. 2a, and Fig. 2b and Fig. 2c show the diagram and luminosity function only for stars of the periphery, where the beginning of the red giant branch is marked (TRGB jump) at $I = 27.^{m}77$, which corresponds to $D = 22.7 \pm 1.4$ Mpc. For more distant galaxies the position of the TRGB jump is very difficult to determine.

For distant galaxies, distances are measured by less accurate methods. The Tully–Fisher relation (TF) is used for spiral galaxies. The accuracy of this method is approximately $0.^{m}4$ [3]. The supernova method (SN Ia) had an accuracy of $0.^{m}65$, but Jha et al. [4] reported that based on multicolor observations they increased the accuracy to $0.^{m}15$. The problem with the supernova method is that supernova flares are rare and have been observed in a limited number of galaxies. The Cepheides relation refers to exact methods, but the measurements obtained by this method cover only a small number of galaxies due to its complexity. It can be stated that for remote galaxies today there are no simple and accurate methods of measuring distances.

Before the advent of the TRGB method, the brightest stars (BS) were widely used. The principle of this method consists of using the relationship between the luminosities of the galaxies and their

Figure 1: HST image of the central part of the interacting galaxy NGC 4038.

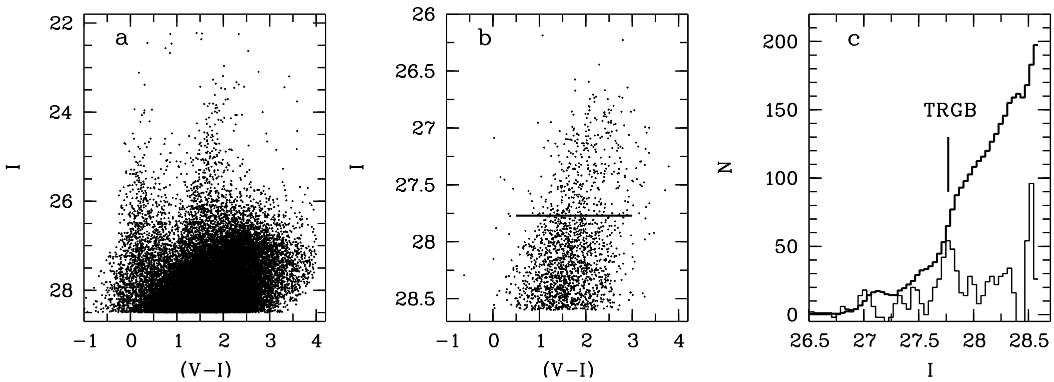

Figure 2: CM diagram of all stars in the NGC 4038 galaxy (a) and the stars of its periphery (b), as well as the luminosity function (c) of these stars, with the beginning of the red giant branch (TRGB jump) indicated at $I = 27.^{m}77$.

brightest stars. This method was proposed in 1919 by Lundmark [5] but it was not used until 1936 when Hubble [6] determined the mean luminosity of the brightest stars for 145 nearby galaxies. The method has been used in 1960s–1990s of the last century ([7–11]). Currently it became possible to update the method of the brightest stars using images of the Hubble Space Telescope. The brightest star method uses young supergiants, which are 4–5 magnitudes brighter than the red giants required for the TRGB method, so the brightest star method can be applied to more distant galaxies.

The main task of the BS-method is to determine the dependence between the luminosities of the galaxies and their brightest stars. Galaxies differ in morphology, luminosity, mass and metallicity of the gas from which stars are born. In addition, galaxies can be members of various spatial structures, groups or clusters that affect the star formation processes and can change the luminosity of the brightest stars. That's why this dependence must be obtained for a large number of galaxies, so that based on a selection of different parameters of galaxies, it would be possible to study this dependence and improve the distance measuring accuracy.

To search for a correlation between the luminosities of galaxies and their brightest stars, we used archival images of the Hubble Space Telescope obtained over many years of its work in various programs. Our sample galaxies are distributed over the M_B luminosity interval from -19^{m} to -8^{m}.

2. Search and Photometry of the Brightest Stars in Galaxies

When searching for the brightest stars in galaxies, some difficulties arise:

1. In distant galaxies, a compact cluster can be taken for a single star.

2. The lifetime of very bright stars is only 2–3 million years, therefore, in low-mass galaxies with limited capabilities of star formation, bright stars may be absent.

3. Background overlay by the stars in our Galaxy over the studied galaxies makes it difficult to search for the brightest stars.

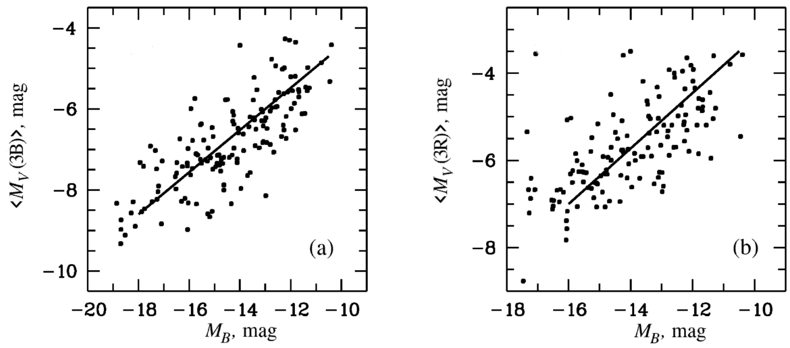

Figure 3: Diagrams of the relationship between the luminosity of galaxies and the luminosity of their brightest blue (a) and red stars (b).

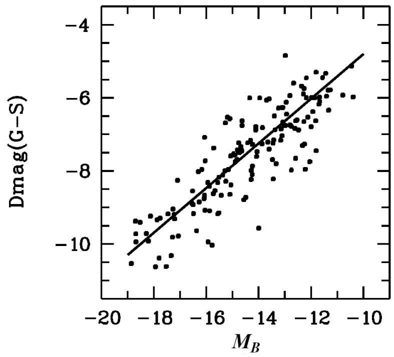

Figure 4: Diagram of the relationship between the absolute luminosity of galaxies and the difference between the apparent magnitude of a galaxy and the mean value of three blue stars.

The stellar photometry of HST images was performed using DAOPHOT II and DOLPHOT 2.0. Distances required to calculate luminosities of the galaxies and their stars were measured by the TRGB method ([1]). More details about this work can be found in the paper by Tikhonov et al. [12]. Star photometry results can be found at:
https://www.sao.ru/hq/dolly/bs/table_1_150.pdf and
https://www.sao.ru/hq/dolly/bs/table_2_150.pdf.

3. Relationship between the Luminosities of Stars and Their Parent Galaxies

Based on the results obtained for 150 galaxies, relations were found between the galaxy luminosities M_B and the average luminosities of three brightest blue $M_V^{(3B)}$ and red $M_V^{(3R)}$ stars. The diagrams (Fig. 3) show that there are linear dependencies (equations (1) and (2)):

$$\langle M_V^{(3B)}\rangle = 0.47 M_B + 0.06, \sigma = 0.38, \quad (1)$$

$$\langle M_V^{(3R)}\rangle = 0.54 M_B + 1.85, \sigma = 0.42. \quad (2)$$

Dependencies (1) and (2) can not be used in this form to determine distances, they need to be modified. The diagram in Fig. 4 shows the dependence between the absolute luminosity of

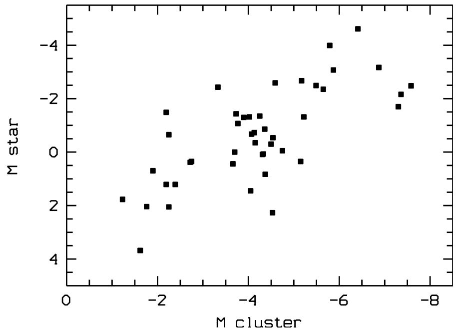

Figure 5: Diagram of the relationship between the absolute luminosity of the Galaxy clusters and absolute luminosities of the brightest stars in these clusters.

the galaxies M_B and the difference between the total apparent magnitude of a galaxy (B_t) and the average apparent magnitude of three blue stars $m_V^{(3B)}$. This dependence makes it possible, by the magnitude difference of the galaxy and stars, to calculate the absolute luminosity of the galaxy and then determine the distance. The dependencies are presented in the form of equations (3) and (4):

$$B_t - \langle m_V^{(3B)} \rangle = 0.61 M_B + 1.31, \sigma = 0.41, \tag{3}$$

$$M_B = \frac{(B_t - \langle m_V^{(3B)} \rangle - 1.31)}{0.61}. \tag{4}$$

Choosing galaxies at different distances, we did not find the influence of the distance effect, that is, for galaxies located closer than 7 Mpc, the deviation of points from the dependence is almost the same as for galaxies at distances up to 20 Mpc.

To study the reasons for the existence of a dependence between the luminosities of galaxies and stars, we have studied the open star clusters of our Galaxy. It turned out that a similar relationship exists for star clusters. On the diagram in Fig. 5 for open star clusters from the Naval atlas of open clusters [13], the dependence between the luminosities of the clusters and their brightest stars is clearly visible.

The obtained results help to explain the origin of the dependence for stars and galaxies. Dwarf galaxies contain low-mass gas and dust clouds; the smaller the galaxy, the smaller the average cloud mass. And in low-mass clouds, there are no conditions for concentration of gas in one high-mass (and hence high luminosity) star. The larger the galaxy, the more massive the clouds and the more massive and luminous the stars in that galaxy. Larson [14] pointed out the relationship between the mass of a molecular cloud and the mass of the most massive star formed. The dependences between the luminosities of galaxies or star clusters and their stars confirm this conclusion.

When using the relationship between the luminosity of galaxies and stars, one can take into account such parameters of galaxies as color index or luminosities in the Hα filter, indicating the activity of star formation processes, so one can reduce the scattering of points using the dependence that we obtained. One can also consider the morphological characteristics of galaxies, their belonging to systems of galaxies of different levels, and instead of luminosity in the blue region, use infrared luminosity, which determines more accurately the mass of a galaxy. Using these additional parameters and not only the luminosity of a galaxy in the blue band, one can improve the distance measurement accuracy.

4. Conclusions

Based on the photometry of 150 galaxies, the dependence between the luminosities of galaxies and their brightest stars is determined. It can be used to calculate distances to irregular and low-mass spiral galaxies: $M_B = (B_t - \langle m_V^{(3B)} \rangle - 1.311)/0.611$. The measurement accuracy according to the proposed dependence is $0.^{m}4$. This most effective method can be used to study the spatial structure of the Virgo cluster, since the HST archive contains a large number of images of galaxies in this cluster that show the brightest stars.

Acknowledgments

The work was performed as part of the SAO RAS government contract approved by the Ministry of Science and Higher Education of the Russian Federation.

References

[1] M.G. Lee, W.L. Freedman and B.F. Madore, *The Tip of the Red Giant Branch as a Distance Indicator for Resolved Galaxies*, Astrophys. J. **417** (1993) 553.

[2] I.S. Jang and M.G. Lee, *The Tip of the Red Giant Branch Distances to Type Ia Supernova Host Galaxies. IV. Color Dependence and Zero-point Calibration*, Astrophys. J. **835** (2017) 28 [1611.05040].

[3] J.A. Willick, *Measurement of Galaxy Distances*, *arXiv e-prints astro-ph* (1996) [astro-ph/9610200].

[4] S. Jha, A.G. Riess and R.P. Kirshner, *Improved Distances to Type Ia Supernovae with Multicolor Light-Curve Shapes: MLCS2k2*, Astrophys. J. **659** (2007) 122 [astro-ph/0612666].

[5] K. Lundmark, *Die Stellung der kugelförmigen Sternhaufen und Spiralnebel zu unserem Sternsystem*, Astronomische Nachrichten **209** (1919) 369.

[6] E. Hubble, *The Luminosity Function of Nebulae. I. The Luminosity Function of Resolved Nebulae as Indicated by Their Brightest Stars*, Astrophys. J. **84** (1936) 158.

[7] E. Holmberg, *A photometric study of nearby galaxies*, *Meddelanden fran Lunds Astronomiska Observatorium Serie II* **128** (1950) 5.

[8] A. Sandage and G.A. Tammann, *Steps toward the Hubble constant. III. The distance and stellar content of the M101 group of galaxies*, Astrophys. J. **194** (1974) 223.

[9] G. de Vaucouleurs, *The extragalactic distance scale. IV. Distances of nearest groups and field galaxies from secondary indicators.*, Astrophys. J. **224** (1978) 710.

[10] R.M. Humphreys, *The brightest stars as extragalactic distance indicators.*, *Astrophys. J.* **269** (1983) 335.

[11] I.D. Karachentsev and N.A. Tikhonov, *New photometric distances for dwarf galaxies in the Local Volume*, *Astron. Astrophys.* **286** (1994) 718.

[12] N.A. Tikhonov, O.A. Galazutdinova, G.M. Karataeva, O.N. Sholukhova, A. Valcheva, V.D. Ivanov et al., *The Brightest Stars of Irregular and Low-Mass Spiral Galaxies*, *Astrophysical Bulletin* **76** (2021) 381 [2112.09917].

[13] A.A. Hoag, H.L. Johnson, B. Iriarte, R.I. Mitchell, K.L. Hallam and S. Sharpless, *Photometry of stars in galactic cluster fields*, *Publications of the U.S. Naval Observatory Second Series* **17** (1961) 344.

[14] R.B. Larson, *Mass spectra of young stars.*, *Mon. Not. R. Astron. Soc.* **200** (1982) 159.