The Brightest Stars of Irregular and Low-Mass Spiral Galaxies

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Received September 3, 2021; revised September 14, 2021; accepted September 14, 2021

Abstract—A search for a correlation between the luminosities of the brightest stars and luminosities of their host galaxies was carried out on archival Hubble Space Telescope (HST) F606W or F555W (V) and F814W (I) images of 150 nearby galaxies. The sample contains only galaxies with ongoing star formation and with known distances we derived with the TRGB-method. We correlated the average absolute luminosities of the three brightest blue and the three brightest red stars with the luminosity of a host. We find a linear relation for both the blue and the red stars in irregular and low-mass spiral galaxies. Their scatters are sufficiently small (0.4) to make these relations useful for distance determination for low-mass galaxies. We found that all 31 dwarf galaxies (M_B > -13) in our sample lack bright massive stars (M_I(B-S) < -7), probably due to the physical conditions that prevent their birth. For galaxies with higher an average luminosity in the range -18 < M_B < -13, there is an asymmetry in the distribution of the number of galaxies relative to the linear dependence, indicating an increase in the fraction of galaxies with bright stars.

Keywords: galaxies: distances and redshifts, galaxies: photometry, galaxies: stellar content
DOI: 10.1134/S1990341321040143

1. INTRODUCTION

There are continuous processes of star formation (SF) in spiral and irregular galaxies, sometimes very active. Violent SF is most often observed in galaxies when they interact with each other at close distances. The masses of young stars are distributed across a wide range according to the Salpeter function (Salpeter, 1955). Here we are only interested in the most massive and brightest of them, because they are readily accessible in other galaxies—typically, with the Hubble Space Telescope (HST)—and can be used as probes of the stellar population and environment there and to find correlations between the parameters of these stars and their hosts. This is a challenging task that requires large samples, to cover the wide parametric space of galaxies—morphologies (spirals or irregulars), luminosities, masses, metallicities, and environment (isolated, groups or clusters members). In this paper, we consider only the correlation between the luminosities of the brightest stars and their host galaxies.

The question of the upper limit to the stellar mass has not yet been resolved. Massive stars evolve very quickly making it difficult to sample them when they are at their brightest stage at the top of the main sequence. Theoretical models suggest that initial stellar masses can be as high as 500 M☉ (Yusof et al., 2013) and more, but so far only stars of much smaller mass have been discovered (Bestenlehner et al., 2020; Crowther et al., 2010; Tehrani et al., 2019). The theory predicts that the brightest and most massive stars should have a low metallicity, therefore, they should be born in dwarf galaxies with low metallicity and violent SF. As a rule, such galaxies are interacting. However, the observations indicate that most of the bright massive stars are located in spiral galaxies (Milky Way, M 31, M 33), and only a few in irregular dwarf galaxies like NGC 6822, SMC, DDO 68, IC 10 (Wofford et al., 2020). Addressing the discrepancy between the theory and observations requires a systematic search and study of bright massive stars in dwarf galaxies.

Further motivation to study the correlations between parameters, e.g. luminosities of the brightest stars and their host galaxies, is the possibility to use these stars and to measure the distances to the host galaxies. This method was proposed by Lundmark (1919), but only in 1936 did Hubble determine the average luminosities of the brightest stars for 145 nearby galaxies (Hubble, 1936). The method was widely used.
in the 1960s—1990s (de Vaucouleurs, 1978; Holmberg, 1950; Karachentsev and Tikhonov, 1994; Sandage and Tammann, 1974). The brightest red supergiants were also used as standard candles to determine the distances to galaxies (Humphreys, 1983; Karachentsev and Tikhonov, 1994). In fact, the red supergiants may be simpler to identify, since they can be easily distinguished from compact young clusters by color.

At present, accurate distances to galaxies within 25 Mpc are obtained using Cepheids (Kenneicutt et al., 1998) or the TRGB method (Tip of Red Giant Branch) (Lee et al., 1993), usually based on images from the Hubble Space Telescope. The TRGB method is efficient, requiring a single epoch, unlike the Cepheid method. Several other methods are invoked for more distant galaxies. The Tully–Fisher relation (Tully and Fisher, 1977) is widely used for spiral galaxies, an average error of distance estimates being 0.4 (Willick, 1996). The SNIa supernova method also has a low accuracy, but Riess et al. (2016) improved it from ±0.65 to ±0.12 by introducing additional corrections. Antipova et al. (2020) demonstrated that the accuracy of this method was ±0.18. Unfortunately the supernovae are rare events occurring randomly in a limited number of galaxies, so the method cannot be applied to preselected objects. Therefore, at present there is no simple and robust method for measuring distances to distant galaxies with an accuracy similar to that of the TRGB method.

The advent of the TRGB for determining distances to galaxies in conjunction with the superb angular resolution of the HST and the development of software for automatic stellar photometry DAOPHOT (Stetson, 1987), DOLPHOT (Dolphin, 2016) pushed the method of the brightest stars into the background.

Historically, the method of brightest stars was used as distance indicators before the TRGB method, but this early development meant that data came from photographic plates. Here we investigate if this technique can be improved. Our effort is driven by a number of considerations. First, the advantages of the HST with the possibilities of software for automatic photometry of large data sets with severely crowded stars DAOPHOT (Stetson, 1987) and DOLPHOT (Dolphin, 2016) allow one to expand the samples beyond what was possible before. To calibrate the brightest stars method, it is necessary to use a large number of galaxies with known distances and accurate photometry of stars. Second, we attempt to introduce additional parameters into the relation between the luminosity of galaxies and their brightest stars, to account for effects like metal abundance and age. We investigate if this reduced the intrinsic scatter of the relation. The improvements can make the brightest stars method relevant for studies of spiral and irregular galaxies beyond 20—25 Mpc, where red giants are not visible in HST images, as well as for very low-mass dwarf galaxies, in which only a small number of blue stars are observed.

2. SEARCH FOR THE BRIGHTEST STARS IN THE GALAXIES

To compare the luminosities of stars and host galaxies we need to find the brightest stars in the galaxies. At first glance, the task seems easy, since bright massive stars (hypergiants) stand out well against the background of other objects. However, most dwarf galaxies simply do not have such stars. The lifetime of very massive objects, which during this period are the brightest stars in galaxies, is extremely short (1—3 Myr), and the probability of their appearance in low-mass galaxies is small. The Salpeter (1955) law predicts that for every 100 M star, several thousand stars of lower masses should form. Even in the spiral galaxies (M 31, M 33, NGC 2403) with numerous star-forming regions, less than 10 bright stars with masses of 150—300 M are known (Richardson and Mehner, 2018; Wofford et al., 2020).

The second difficulty is the contamination by foreground stars from our Galaxy. The vast majority of background stars have color indices (V − I) = 0.8—1.2, but sometimes there are blue background stars that do not differ in color from young stars of the galaxy under study. Tikhonov et al. (2021) reported an example in the low-metal dwarf galaxy DDO 68, demonstrating that although the foreground contamination probability for a sample of candidates for massive stars is low, it is not zero.

Next, most massive stars are born in clusters (de Wit et al., 2004) and are more likely—but not exclusively—to be found still residing there, so searches for the brightest stars should concentrate on young star clusters, where the crowding and the contamination problems are more severe than in the field. Challenging the searches further, the third difficulty is brought up by the insufficient angular resolution of the ground based telescopes, even for targets in our Galaxy. HST dramatically improves the angular resolution of images, but it is not enough for more distant galaxies. In fact, unresolved clusters were sometimes taken for single bright stars, as shown early on by Sandage (1958). To identify bright hypergiants one can use their variability and their strong H emission. However, these require time consuming multi-epoch observations and spectroscopy, rendering the task of finding the brightest stars in several hundred galaxies nearly impossible.

Here we report the brightest stars in a large sample of galaxies circumventing most of the challenges listed above by means of the superb angular resolution of HST. It allows distinguishing between the massive stars and the nearby stars, to carry out reliable pho-
tometry, determining their brightness and color. To exclude compact star clusters the candidates for the brightest star were visually inspected and their photometric profiles were compared with the profile of bona-fide single stars. Compact H II regions were detected by their blue color.

The search for bright red stars in galaxies suffers from other problems—for example, a contamination due to red dwarfs from our Galaxy. The stars of the galaxy are expected to concentrate towards the center, whereas the foreground stars should be evenly distributed. The positions of bright red stars can give a hint to their nature—the massive stars in the galaxy are likely to appear in regions of active SF. The proper motions—e.g. from Gaia (Brown, 2021)—may provide another method for identifying the contaminating objects.

The different stellar populations, selection procedures and contamination levels led to a different number of galaxies with red and with blue stars in our final sample.

3. SAMPLE OF GALAXIES AND DISTANCES TO THEM

We assembled archival HST WFPC2, WFC3 and ACS images in $F435W$, $F555W$, $F606W$ and $F814W$ filters (throughout the paper we will refer to them as $B$, $V$ and $I$, respectively), obtained over many years, mainly for projects to determine distances to galaxies. The 150 host galaxies in our sample are distributed in the $M_B$ luminosity range from $-19$ to $-8$. We did not include very close galaxies (M 31, M 33, and others), since their angular sizes were much larger than the field sizes of the ACS camera of HST, and the limited coverage raises the issue of completeness. For some galaxies we used two fields to cover all the bright stars in the galaxies, but the results in the vast majority of cases are obtained by one field photometry (Fig. 1). Galaxies with partial coverage were excluded. The sample is dominated by irregular and spiral galaxies. Typically, the distances to them fall within the 5–15 Mpc range. The complete list of galaxies is given in Table 1, but more galaxies will be added later.

For three galaxies only images in $F435W$ and $F814W$ were available, we derived magnitudes in the missing filter based on the relations between $F606W-F814W$ and $F435W-F814W$ for galaxies of a similar types.

Distances for some galaxies in the sample have not been reported in the literature (see Tikhonov (2018)). We took advantage that the red giants are reliably identified in all galaxies in our sample and for these objects we derived distances with the TRGB method (Lee et al., 1993) for the entire sample, for uniformity. We

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1 https://www.sao.ru/hq/dolly/bs/table_1_150.pdf.
excluded the central regions of galaxies to avoid problems related with crowding, contamination by red supergiants and internal extinction in the host galaxy. We applied the calibration of Lee et al. (1993), and determined the position of the TRGB jump with the Sobel filter (Madore and Freedman, 1995). The foreground Milky Way extinction was taken from Schlafly and Finkbeiner (2011).

To gain confidence in our results we repeated this measurement for the rest of the sample and our values agree well with the literature estimates (Tikhonov, 2018).

4. STELLAR PHOTOMETRY

The stellar photometry on the ACS and WFPC2 images was performed with DAOPHOT II (Stetson 1987, 1994), and on the WFC3 images—with DOLPHOT 2.0. We followed the best practices as described in Tikhonov et al. (2019), in Holtzman et al. (1995a, b) and Dolphin (2016), for each of the three instruments, respectively. The basic steps included: bad pixel masking, cosmic ray hit removal and PSF photometry. For DAOPHOT we built the PSF from single isolated field stars, and in DOLPHOT we used a PSF profile library. Both methods yield identical results for the positions of TRGB.

Next, we identified and removed the non-stellar objects like star clusters and compact distant galaxies, according to the CHI and SHARP parameters (Stetson, 1987). An example CMD is shown in Fig. 1. For each galaxy we identified the three brightest blue and red stars were (Fig. 2). Their average magnitudes and colors are presented in Table 2.

5. GALAXIES AND THEIR BRIGHT STARS

We calibrated the relationship between the $M_B$ luminosities hosts and the average luminosities of three brightest blue and red stars in the $V$ filter, $M_B(BS)$ and $M_B(RS)$ respectively (Fig. 3) and obtained linear relations for low and medium luminosities (Table 2).
As it was pointed above, the brightest and most massive stars should be observed in galaxies with low metallicities (Yusof et al., 2013). Low-metal galaxies can only be dwarfs, in which the SF process occurs in individual irregular flares, so such galaxies should have a maximum spread in the star luminosities, from the brightest hypergiants to normal main sequence stars. However, in the diagram in Fig. 3a we do not see an excessive population of very bright blue stars in faintest, and presumably most metal poor galaxies with $-13^m < M_B < -10^m$. If we consider this diagram in the

![Fig. 3. Relationship between the average luminosities of the brightest three blue (a) and red (b) stars and the luminosity of their host galaxy.](image)

| Number | Galaxy       | $m^B_V$ | $(V-I)^B$ | $\langle m^B_V \rangle$ | $\langle (V-I)^B \rangle$ | $m^R_V$ | $(V-I)^R$ | $\langle m^R_V \rangle$ | $\langle (V-I)^R \rangle$ |
|--------|--------------|---------|-----------|-------------------------|--------------------------|---------|-----------|-------------------------|--------------------------|
| 1      | AGC 102728   | 24.398  | 0.101     | 24.535                  | 0.099                    | 23.333  | 1.513     | 24.404                  | 1.583                    |
| 2      | ESO 349-031  | 20.711  | -0.049    | 21.125                  | -0.022                   | 21.184  | 1.529     | 22.055                  | 1.600                    |
| 3      | NGC 24       | 22.214  | 0.085     | 22.380                  | 0.119                    | 23.671  | 1.451     | 24.057                  | 1.493                    |
| 4      | UGC 288      | 22.914  | -0.088    | 23.209                  | 0.031                    | 24.410  | 1.668     | 24.709                  | 1.611                    |
| 5      | IC 1574      | 22.550  | 0.290     | 22.671                  | 0.113                    | 22.084  | 1.500     | 22.182                  | 1.503                    |
| 6      | DDO 6        | 22.441  | 0.267     | 22.634                  | 0.244                    | 23.235  | 2.855     | 23.566                  | 2.881                    |
| 7      | IC 1613      | 18.787  | 0.121     | 18.774                  | -0.060                   | 19.297  | 1.634     | 19.595                  | 1.575                    |
| 8      | UGC 685      | 20.401  | 0.016     | 21.193                  | 0.045                    | 22.742  | 1.701     | 22.992                  | 1.560                    |
| 9      | KKH 6        | 22.124  | 0.711     | 22.689                  | 0.718                    | 22.845  | 2.566     | 23.562                  | 2.278                    |
| 10     | PGC 6430     | 21.774  | 0.260     | 21.955                  | 0.150                    | 21.888  | 1.500     | 22.087                  | 1.507                    |
region of brighter galaxies \((-18^m < M_B < -13^m)\), then an increase in the number of outliers corresponding to galaxies with higher luminosity is noticeable—these are the points below the linear fit in Fig. 3a. The effect is more obvious in Fig. 4, which shows the distributions of residuals with respect to the linear fits (1) for blue stars. Low luminosity galaxies \((-13^m < M_B < -10^m)\) have a symmetric scatter, with no excess of galaxies with bright stars. But galaxies of average luminosity \((-18^m < M_B < -13^m)\) show asymmetric distribution with a tail comprised of galaxies with relatively bright stars respectively to the relation (1).

This result has a simple explanation. The faintest galaxies are galaxies without intense SF processes and one should not expect the appearance of very bright stars in them. They have insignificant masses of hydrogen and low-mass clusters are formed in the SF process. Therefore, the birth of a supermassive brightest star in such a galaxy is unlikely. The more massive galaxies \((-18^m < M_B < -13^m)\) have enough hydrogen, and their metallicity is still low compared to the metallicity of massive spiral galaxies, so one can expect the formation of supermassive stars in them. With active SF processes, the luminosity of galaxies increases, especially in the blue, due to the appearance of young blue stars, therefore, during an outbreak of SF, when the birth of bright massive stars occurs, the galaxy itself has an increased brightness. This can be seen in the diagram in Fig. 4, where the distribution asymmetry, that is, the appearance of high-brightness stars, is observed in galaxies with \(-18^m < M_B < -13^m\).

6. DISCUSSION

To facilitate distance determination we converted relation (1) to a relation between the difference of the apparent stellar magnitude of the galaxy and the average apparent stellar magnitude of three blue stars and the absolute luminosity of galaxies (Fig. 5):

\[
D\text{mag}(GS) = B_i - \langle m^B_{i} \rangle
\]

and the absolute luminosity of \(M_B\) galaxies (Fig. 5):

\[
B_i - \langle m^B_{i} \rangle = 0.611 M_B + 1.311, \quad \sigma = 0.41, \quad (3)
\]

or inverted:

\[
M_B = \frac{(B_i - \langle m^B_{i} \rangle - 1.311)}{0.611}. \quad (4)
\]

We did not find a noticeable change of the scatter with distance, implying that systematic effects like cluster contamination can reliably be removed by the superior angular resolution of HST up to the distance range covered by our sample.

The last relation makes it possible to calculate directly the absolute luminosity of the galaxy \(M_B\) from the difference in the magnitudes of the galaxy and the brightest stars. The distance modulus is

\[
(m - M) = B_i - M_B.
\]
and the distance is

\[ \log D = (m - M)/5 + 1 \text{ (pc)} \]

It should be remembered that \( B_t \) and \( \langle m^B \rangle \) were corrected for foreground Milky Way extinction according to Schlafly and Finkbeiner (2011).

Similarly red stars can be used for the same purpose, but the derived relation shows more scatter and the accuracy of the derived distance is worse. Furthermore, the blue stars are easier to distinguish from the field stars in the host, and they do not suffer from foreground contamination by Milky Way stars where the faintest stars are significantly redder. In addition, in small dwarf galaxies with star-forming regions harbor more blue stars than red stars, so choosing blue stars increases the statistical base of these measurements.

7. SUMMARY AND CONCLUSIONS

The brightest blue and red stars were identified in 150 irregular and low-mass spiral galaxies based on HST imaging. Distances were determined for the entire sample using the TRGB method. We calibrated the relation between the average absolute luminosity of the three brightest stars and the absolute luminosity of the host galaxies.

There is apparent lack of bright stars in fainter galaxies: the galaxies with a luminosity \(-16^m < M_B < -15^m\) have bright stars, none of the 31 faint galaxies have bright stars, although the total luminosity of faint galaxies is \( M_B = -15.5^m \). Earlier, it was believed that the formation of brighter stars in more massive galaxies is explained only by a larger number of stars than in small galaxies, so the upper end of the initial mass function would be better populated. But our result suggests that this lack of bright stars may be due to other reasons, e.g. the physical conditions and the mechanism of formation of bright massive stars in galaxies of low mass, rather than a statistical sampling effect.

Finally, we derived a linear relationship, suitable for galaxy distance determination from the brightest blue stars:

\[ M_B = (B_t - \langle m^B \rangle - 1.311)/0.611. \]

It suffers from a significant scatter (\( \sigma = 0.41^m \)), but this can be reduced by parameterizing the residuals with color indices of galaxies or Hα flux, to reflect the intensity of the ongoing SF. These opportunities are beyond the scope of our work, but will be investigated in the future.

Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc. under contract no. NAS5-26555. These observations are associated with the proposals 5091, 5375, 5397, 5427, 5915, 5971, 5972, 6431, 6549, 6584, 6695, 6865, 7202, 7496, 8059, 8061, 8601, 9042, 9086, 9162, 9765, 9771, 9774, 9820, 10182, 10210, 10235, 10402, 10427, 10433, 10438, 10505, 10523, 10585, 10605, 10696, 10765, 10877, 10885, 10889, 10905, 10915, 10918, 11229, 11307, 11360, 11575, 11718, 11986, 12196, 12546, 12878, 12880, 12902, 12968, 13357, 13364, 13442, 13750, 14678, 15133, 15243, 15275, 15564, 15605, 15696, 15765, 16075.

FUNDING

The study was financially supported by the Russian Foundation for Basic Research and the National Science Foundation of Bulgaria as a part of the scientific project no. 19-52-18007 and Bulgarian NSF project KP-06-Russin-09/2019.

CONFLICT OF INTERESTS

The authors declare no conflicts of interest.

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