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Searching for the brightest stars in galaxies outside the Local Group

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Abstract This paper introduces a technique for searching for bright massive stars in galaxies beyond the Local Group. To search for massive stars, we processed the results of stellar photometry from the Hubble Space Telescope (HST) images using the DAOPHOT and DOLPHOT packages. The results of such searches are demonstrated with examples of the galaxies DDO 68, M94 and NGC 1672. In the galaxy DDO 68, the LBV star changes its brightness, and massive stars in M94 can be identified by excess in the Hα band. For the galaxy NGC 1672, we measure the distance for the first time by the TRGB method, which enabled determining the luminosities of the brightest stars, likely hypergiants, in the young star formation region. So far, we have performed stellar photometry on HST images of 320 northern sky galaxies located at a distance less than 12 Mpc. This allowed us to identify 53 galaxies with probable hypergiants. Further photometric and spectral observations of these galaxies are planned to search for massive stars.

Key words: stars: massive — stars: variables: LBV — galaxies: individual: M94, DDO 68, NGC 1672

1 INTRODUCTION

One of the main tasks of modern astrophysics is to determine the upper limit on the mass of a star. The interest lies in the fact that massive stars evolve quickly and the final stage of their evolution can be a supernova burst, formation of a black hole or a neutron star, or even a merger of such relativistic objects with the release of a huge amount of energy. The evolutionary path of a star depends on its initial mass. Models of stellar evolution suggest that the initial masses of stars can reach up to 500 solar masses (Yusof et al. 2013; Spera & Mapelli 2017) or more, but so far, only the stars with much smaller mass have been discovered (Crowther et al. 2010). The question regarding the fidelity of theoretical models can only be solved by searching for and studying massive stars in galaxies with various masses.

In our Galaxy, massive stars are observed in clusters located in the galactic plane, where the extinction of light can be very high (Eikenberry et al. 2004). To increase the breadth of the search and solve the problem related to the uncertainty of light extinction, one should go beyond the Galaxy and search for massive stars in other, not too distant galaxies (Humphreys et al. 2017; Sholukhova et al. 2018). Using the Hubble Space Telescope (HST), numerous galaxies outside the Local Group are accessible for study (up to distances of 15–20 Mpc).

2 SEARCH FOR CANDIDATES OF MASSIVE STARS

Spectral observations enable determining the type of star and evaluating its physical parameters, but such observations are not suitable for search tasks because of the large number of candidates of massive stars and high time expenditures to obtain the results. Therefore, to identify possible candidates for massive stars (hypergiants), photometric methods are employed, as they are faster and more accessible on all telescopes.

It seems that finding massive stars, which are also the brightest stars in galaxies, is not difficult, but this assertion is incorrect. In many low-mass galaxies, there are simply no such stars. The lifetime of these stars is very short (several million years), and the frequency of their appearance in galaxies is small. According to Salpeter's initial mass distribution, thousands of stars with smaller masses should be born per star with a mass of 100

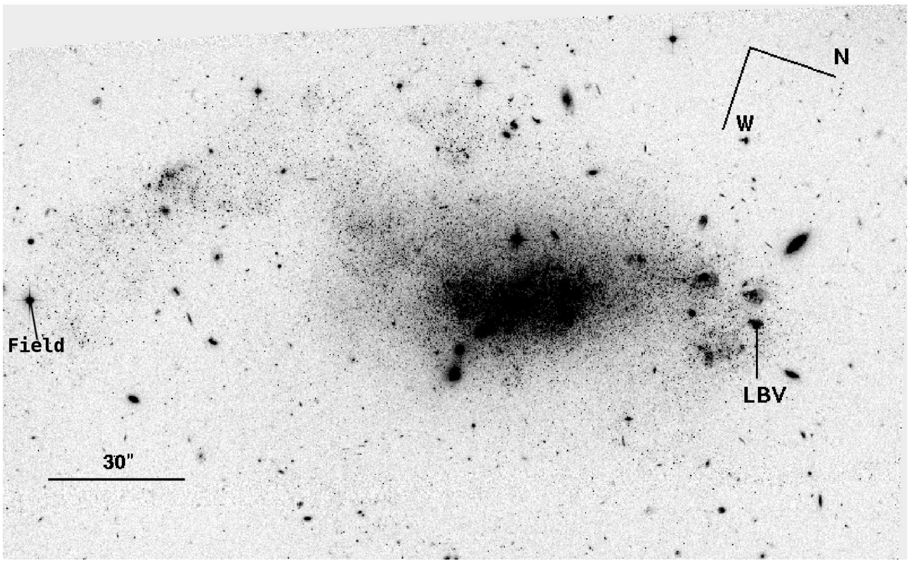

Fig. 1 Dwarf metal-poor galaxy DDO 68 in the F606W (V) filter with the LBV star, marked by a circle and a bright blue field star belonging to our Galaxy.

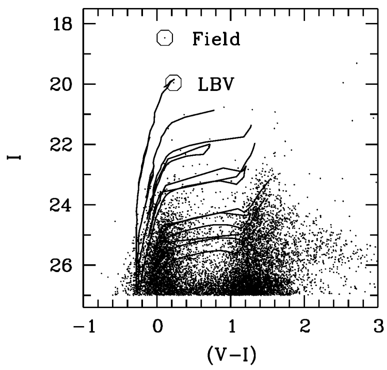

Fig. 2 CM diagram of DDO 68 stars and isochrones with age from 3 Myr to 100 Myr and metallicity $Z = 0.001$ from Bertelli et al. (1994). The positions of the LBV star and the foreground star are marked.

solar masses. Even in our giant Galaxy, with numerous star formation regions, only a few stars with masses of 150—300 solar masses are known including HD 15558 A (Garmany & Massey 1981) and Eta Carinae (Gull 2015).

The second factor that complicates the search is the superposition of stars of our Galaxy on the studied fields. An example is given by the metal-poor dwarf galaxy DDO 68 (Fig. 1), the distance to which is 12±0.3 Mpc (Tikhonov et al. 2014). In this galaxy, a bright massive luminous blue variable (LBV) star has been identified (Pustilnik et al. 2017), which is marked on the image of the galaxy (Fig. 1). On the Hertzsprung-Russell diagram (also called the color-magnitude diagram or CM diagram) for DDO 68 (Fig. 2), this star is very bright (according to our measurements, $M_V = -10\overset{\text{m}}{.}26$). However, this CM diagram contains another brighter blue star, also visible in the body of the galaxy (Fig. 1). As affirmed by spectral observations with the 6-m telescope Big Telescope Alt-Azimuth (BTA), this bright blue star has no emission lines, and its radial velocity is low compared to DDO 68. This indicates that it is not a massive star in DDO 68, but rather belongs to our Galaxy. Isochrones of Bertelli et al. (1994) overplotted on the DDO 68 CM diagram also reveal that the bright blue star does not belong to the stars in DDO 68. Thus, the probability of a foreground star falling into the selection of candidates for massive stars is far from zero.

A convenient feature for identifying foreground stars is to compare the positions of bright stars with respect to star formation regions. The probability that a massive star will appear in a star cluster is always higher than the probability of its isolated appearance. A comparison of the positions of two bright blue stars in the DDO 68 galaxy indicates that the LBV star is indeed surrounded by a cluster of stars and gas clouds, but the foreground star is completely isolated. However, this feature is not absolutely mandatory, since bright massive stars are known outside of clusters.

The third factor that impedes the search is the insufficient spatial resolution of telescopes. Even in our Galaxy, when relying on ground-based telescopes, it is not possible to separate close groups of massive stars into separate stars. Therefore, when the mass of the entire group of stars is attributed to a single star, errors in mass estimation can occur. The HST allows separating close groups and evaluating the luminosities of individual stars, but it is still not enough for distant galaxies.

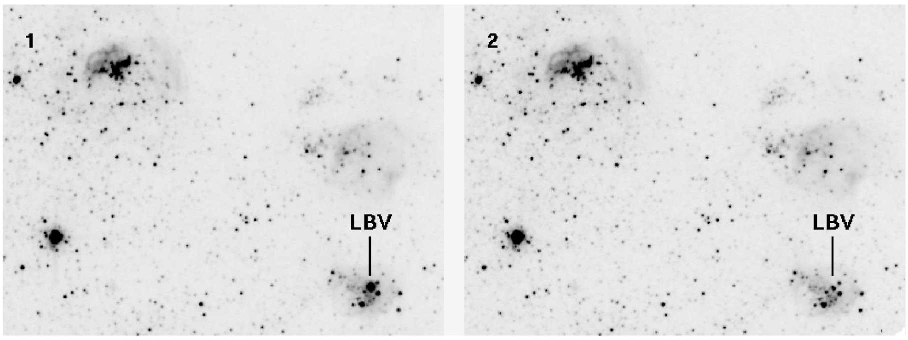

Fig. 3 Images of the galactic region DDO 68 in 2010 and 2017 in the F606W filter, in which the LBV star is marked by a line. A large change in the luminosity of the LBV star over 7 years can be seen.

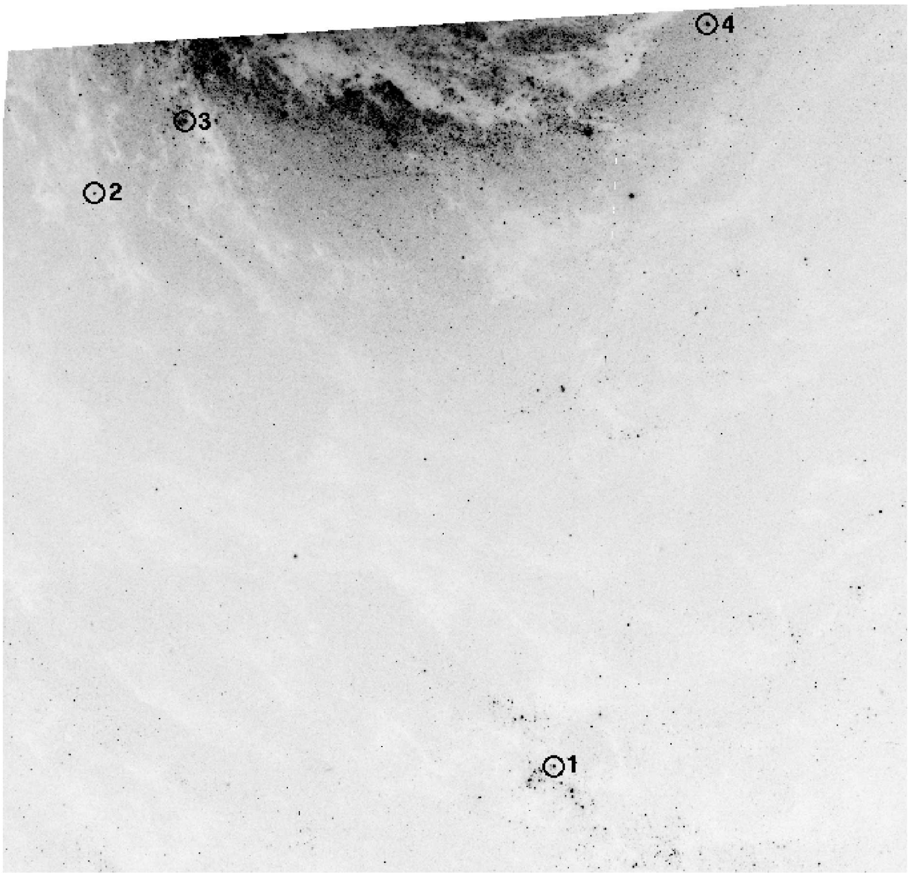

Fig. 4 Part of the galaxy M94 in an HST image in the F555W filter. The positions of four bright blue stars with increased brightness in the Hα filter are marked.

The unstable state of massive stars often leads to variability in their brightness, which can be exploited to search for such stars. However, constancy in the brightness of a star over several years does not mean it is stable for a longer time interval. Only a long series of accurate photometric measurements can provide an answer about brightness variability. Figure 3 displays the images of the LBV star in DDO 68 in 2010 and 2017. The pictures clearly exhibit a strong drop in its brightness from $V = 20\overset{\mathrm{m}}{.}19$ (2010) to $V = 23\overset{\mathrm{m}}{.}70$ (2017) (from $M_V = -10\overset{\mathrm{m}}{.}26$ to $M_V = -6\overset{\mathrm{m}}{.}75$).

Due to the instability of massive stars, gas loss occurs and various shells and clouds form. In the spectra of such stars, a strong Hα hydrogen emission line should be observed. The presence of the emission line greatly simplifies the search for candidates of massive stars. Images of the galaxy in Hα filter, together with images in other filters (F435W, F555W, F606W and F814W) allow us to highlight bright blue stars with Hα emission, which

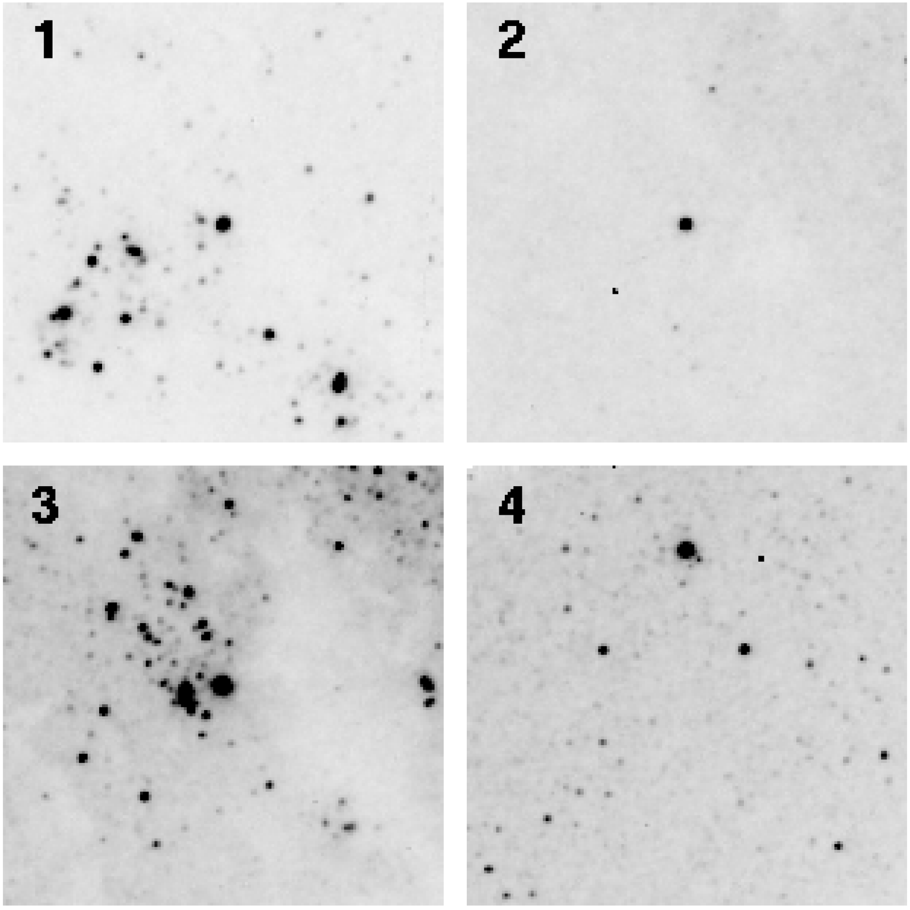

Fig. 5 Regions of stars marked in Fig. 4 with numbers. Star N4 is shown off-center.

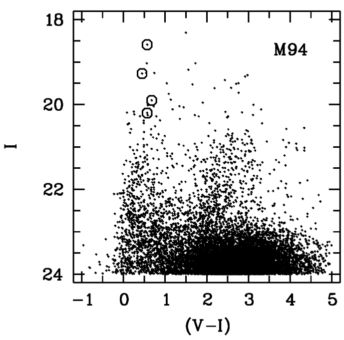

Fig. 6 CM diagram of the field of the galaxy M94. Among the bright blue objects are both massive stars and possible young compact clusters.

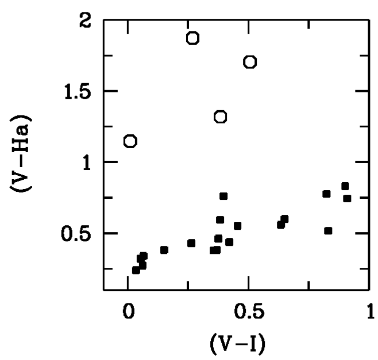

Fig. 7 CM diagram of bright blue stars seen in the diagram in Fig. 6. Black squares signify stars without emission in the Hα line, and circles — stars with emission. These stars are marked on the image of the galaxy (Fig. 4).

are likely to be the sought-after massive stars. But even after such a selection, extraneous objects fall into the list. Young compact star clusters almost do not differ in terms of their profile from single stars; they have strong Hα emission and a small color index, identical to the color index of bright massive stars. High resolution spectral observations help to separate stars from clusters, but this requires additional research.

3 SEARCH FOR MASSIVE STARS IN THE GALAXIES M94 AND NGC 1672

Figure 4 displays an HST image of a part of the galaxy M94. Stellar photometry of this galaxy was performed with

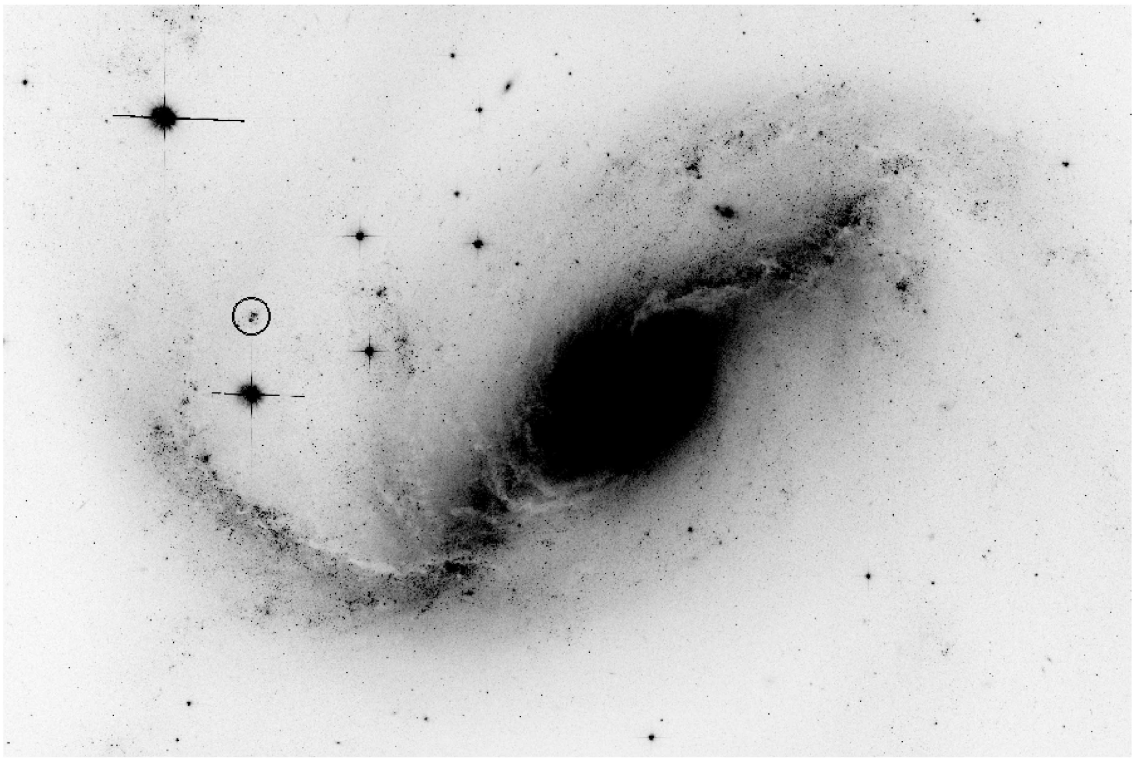

Fig. 8 Galaxy NGC 1672 in the HST image in the F814W filter. The circle marks the position of the gas and dust nebula and star cluster containing stars up to $M_V = -10$.

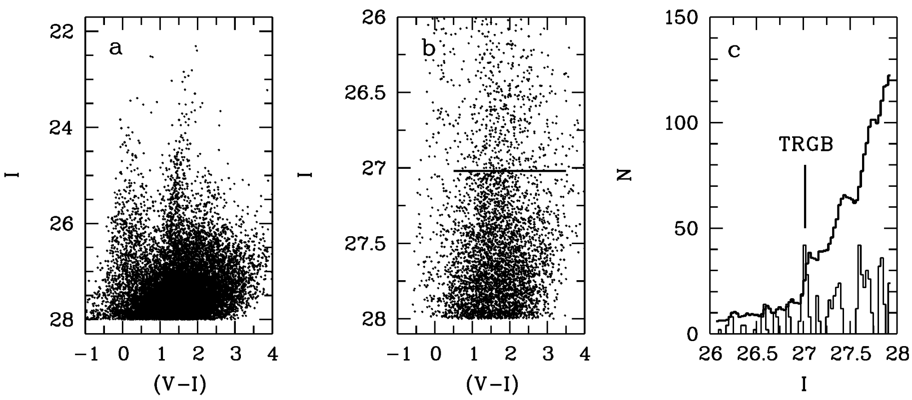

Fig. 9 CM diagram of stars in the periphery of NGC 1672 (a) and CM diagram in the same field as (b) after stars from star-formation regions are removed. The luminosity function of red giants and asymptotic giant branch (AGB) stars (c) was obtained after selecting stars with the color index $(V - I)$. The thin line indicates the Sobel function, signifying the increase in the number of stars (TRGB jump) at $I = 27\overset{\text{m}}{.}02$.

the DOLPHOT 2.0 software package[1]. The DOLPHOT 2.0 package was employed in accordance with Dolphin's recommendations (Dolphin 2016), while the photometry procedure consisted of bad pixel premasking, removal of cosmic-ray particle hits and further PSF photometry for the stars found in two filters. The photometry parameters utilized in our work can be referenced[2]. The obtained results of stellar photometry were selected according to the parameters $CHI < 1.3$ and $|SHARP| < 0.3$, which define the shape of the photometric profile of each measured star. This allowed us to remove all diffuse objects (star clusters, distant or compact galaxies) from the photometry tables, because the photometric profiles of these objects differed from those of stars.

After applying the DOLPHOT 2.0 package to the images taken with the WFC3/UVIS camera, we get the results of VegaMag photometry, which differ from the

[1] `http://americano.dolphinsim.com/dolphot/dolphot.pdf`

[2] `https://cloud.mail.ru/public/Gw6v/FvP1sRmKr`

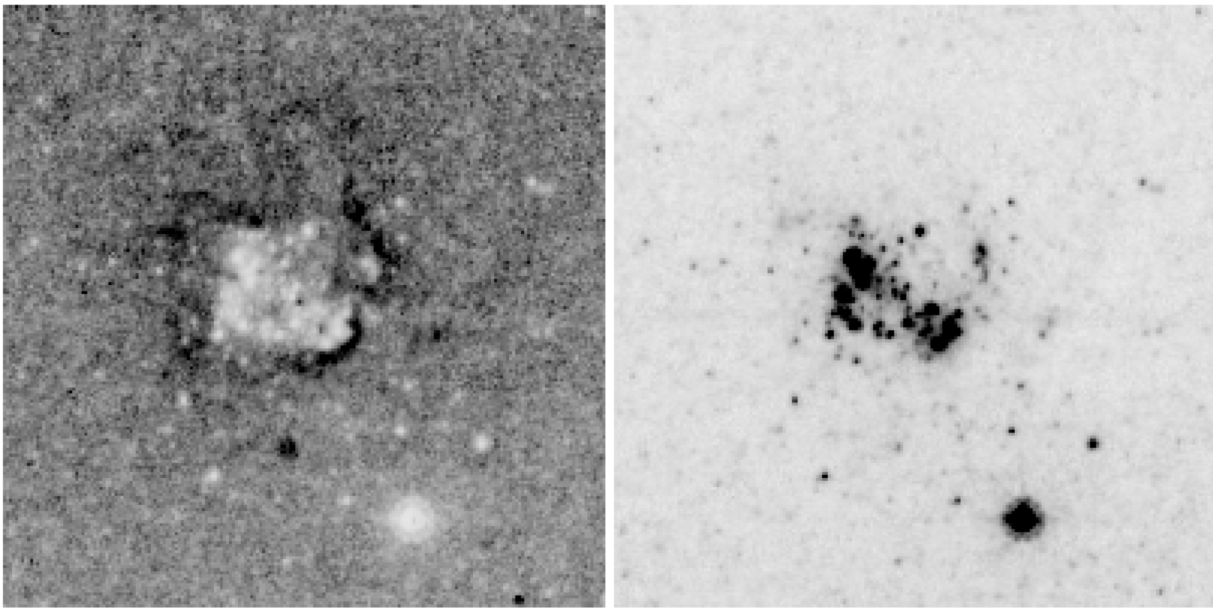

Fig. 10 *Left*: nebula and star cluster extracted from Fig. 8. The image was obtained by dividing by images from the filters F658N and F814W. There is a visible gas shell around the cluster that has not dispersed due to the youth of the cluster. *Right*: the same cluster in filter F814W.

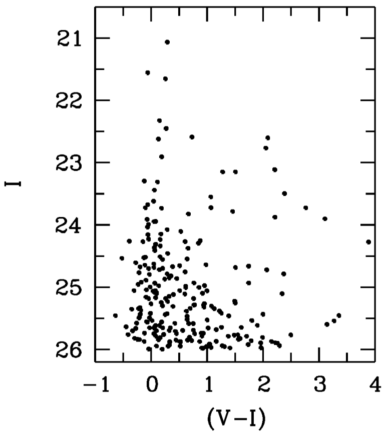

Fig. 11 CM diagram of a young cluster from NGC 1672.

Johnson–Cousins system. However, when DOLPHOT 2.0 photometry of the ACS camera images was examined, we obtained results for the stars in both the VegaMag and Johnson–Cousins systems. Therefore, it is not difficult to translate magnitudes from one system to another. In addition, for blue LBV stars, the differences between the systems are very small and do not even exceed the photometry error (i.e., less than $0^{\rm m}\!.02$).

We tested a method for identifying probable massive stars based on photometry of galaxies in several filters. The HST archive contains images of the galaxy M94 (ID10402) obtained in the F435W, F555W, F658N and F814W filters with exposures of 1200, 1000, 1400 and 900 s. In this galaxy, a visual search for massive stars has already been carried out and three probable LBV stars have been found (Solovyeva et al. 2019).

The CM diagram, obtained after photometry of stars in M94 was performed, is featured in Figure 6. Bright blue stars are highlighted on the diagram. An additional diagram using photometry in the Hα filter (Fig. 7) makes it possible to distinguish four blue stars with the possible presence of Hα emission lines in the spectrum. The regions of these stars are displayed with an enlarged scale in Fig. 5.

Stars that do not have excess in Hα are marked in the diagram (Fig. 7) with black squares. They are not of interest, although their luminosity may be even higher than that of stars with emission in Hα.

Spectra for three stars with Hα emission (Fig. 6) were obtained during observations at the 6-m BTA (Solovyeva et al. 2019), which confirmed the presence of the Hα line. These three stars change their luminosity and can be considered as LBV stars. No spectral observations were performed for the fourth star, but it can be assumed that this star also belongs to the class of bright massive stars.

The results of photometric search for massive stars in M94 have affirmed that such stars can be identified by examining images in several filters.

The Seyfert galaxy NGC 1672 (Fig. 8) is probably part of the Dorado group (Shobbrook 1966). Uncertainty arises from unreliable determination of distance. Using archival images acquired by HST (ID10354 and ID15654), we performed stellar photometry on this galaxy with the

DAOPHOT II (Stetson 1987, 1994) and DOLPHOT 2.0 software packages. The selection of stars in DAOPHOT II was carried out in the same way as in DOLPHOT 2.0: $CHI < 1.3$ and $|SHARP| < 0.3$. The resulting CM diagram of NGC 1672 stars is featured in Fig. 9(a); Fig. 9(b,c) demonstrates the luminosity function, which marks the tip of the red-giant branch (TRGB) jump, and is necessary to determine the distance to the galaxy.

The obtained distance value ($D = 15.8 \pm 0.8$ Mpc) confirms that NGC 1672 belongs to the Dorado group. The obtained distance allows us to measure the energy of the galactic nucleus, and to determine the luminosities of the brightest stars, which are visible on the obtained CM diagram (Fig. 9).

In Figure 8, a circle indicates a young star cluster surrounded by a gas shell (Fig. 10) and containing stars up to $M_V = -10$. The CM diagram of this young cluster (Fig. 11) does not differ from similar diagrams of other clusters. Therefore, we believe that most of the stars in this diagram are single stars and not a cluster of stars. This young cluster is similar to the R136 cluster in Large Magellanic Cloud (LMC), where very massive stars are located.

Whether bright stars in the cluster NGC 1672 are single or multiples can only be determined from additional observations. Variability in the brightness of these stars would indicate that they are single stars. It should be noted that the stability of brightness does not prove that these stars are multiples or star clusters.

4 CONCLUSIONS

The briefly described methods of searching for candidates of hypergiants are used by us for galaxies outside the Local Group. After compiling a list of likely massive stars, we make spectral observation with the 6-m BTA facility and obtain more detailed information about physical parameters of the stars. Not every galaxy contains bright hypergiants. To increase the area of the search for massive stars, we performed stellar photometry on the HST images of 320 galaxies in the northern sky. Possible hypergiants have been found in 53 galaxies. Planned spectral and photometric observations with ground-based telescopes will help us to identify massive stars in these galaxies.

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References

Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275

Crowther, P. A., Schnurr, O., Hirschi, R., et al. 2010, MNRAS, 408, 731

Dolphin, A. 2016, DOLPHOT: Stellar photometry (Astrophysics Source Code Library, record ascl:1608.013)

Eikenberry, S. S., Matthews, K., LaVine, J. L., et al. 2004, ApJ, 616, 506

Garmany, C. D., & Massey, P. 1981, PASP, 93, 500

Gull, T. R. 2015, in Wolf-Rayet Stars, eds. W.-R. Hamann, A. Sander, & H. Todt, 149

Humphreys, R. M., Davidson, K., Hahn, D., et al. 2017, ApJ, 844, 40

Pustilnik, S. A., Makarova, L. N., Perepelitsyna, Y. A., et al. 2017, MNRAS, 465, 4985

Shobbrook, R. R. 1966, MNRAS, 131, 365

Sholukhova, O. N., Fabrika, S. N., Valeev, A. F., & Sarkisian, A. N. 2018, Astrophysical Bulletin, 73, 413

Solovyeva, Y., Vinokurov, A., Fabrika, S., et al. 2019, MNRAS, 484, L24

Spera, M., & Mapelli, M. 2017, MNRAS, 470, 4739

Stetson, P. B. 1987, PASP, 99, 191

Stetson, P. B. 1994, PASP, 106, 250

Tikhonov, N. A., Galazutdinova, O. A., & Lebedev, V. S. 2014, Astronomy Letters, 40, 1

Yusof, N., Hirschi, R., Meynet, G., et al. 2013, MNRAS, 433, 1114