HST WFPC2 OBSERVATIONS OF THE PECULIAR MAIN SEQUENCE OF THE DOUBLE STAR CLUSTER NGC 2011 IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

We report the serendipitous discovery of a peculiar main sequence in archived Hubble Space Telescope Wide Field Planetary Camera 2 (WFPC2) observations of the young star cluster NGC 2011 in the Large Magellanic Cloud. The bright part of this main sequence exhibits a prominent double, forklike feature, as if it consists of twin main sequences, one of them being redder. The color-magnitude diagram, constructed from the stars found in the only available WFPC2 field of the cluster, is used to distinguish the stars according to their membership to each of these sequences and to study their spatial distribution. We find that there are two well-distinguished populations in the sense that the redder main sequence is dominated by stars that belong to the main body of the cluster, while the stars of the bluer main sequence belong to the surrounding region. Providing that NGC 2011 is a verified binary cluster, with the second companion unfortunately not observed, and taking into account the general region where this cluster is located, we discuss the possible scenarios from both star formation and an early dynamical evolution point of view that might explain this unique discovery.

Subject headings: galaxies: star clusters — globular clusters: individual (NGC 2011) — Hertzsprung-Russell diagram — Magellanic Clouds — stars: evolution

1. INTRODUCTION

The Large Magellanic Cloud (LMC) contains an extraordinary sample of star clusters with a large variety in spatial distribution, age, and luminosity (e.g., Kontizas et al. 1990; Bica et al. 1999). This intriguing population of clusters include peculiar types of systems, like binary and elliptical clusters, that we do not see in the Galaxy. In this Letter we present our findings from Hubble Space Telescope (HST) observations of the LMC cluster NGC 2011 with the Wide Field Planetary Camera 2 (WFPC2). NGC 2011 is a young star cluster with age 6 (± 1) Myr (Elson & Fall 1988) located in a young region (Fig. 1, left) at the southern edge of the supergiant shell LMC 4 (Meaburn 1980). It is considered to be one of the brightest and most populous double clusters in the LMC (Kontizas et al. 1989). It was originally identified as a probable double cluster by Bhatia & Hatzidimitriou (1988), who conclude that among the LMC cluster population binary clusters constitute a statistically significant sample.

The multiplicity of the cluster, in the sense that projection effects cannot account for this pair, was verified by Kontizas et al. (1993), who studied the stellar content in the outer region of the cluster by means of spectra classification from UK Schmidt objective prism spectra, and in the core of the cluster with low-resolution International Ultraviolet Explorer (IUE) spectra. From the spectral classification it was found that both members of the pair show identical stellar content, dominated by early-type stars, quite different from the stellar component of the neighboring field, where stars with spectral type later than A dominate. The UV-integrated spectra taken with IUE showed that the stellar content in the core of both the brighter (named NGC 2011a) and fainter (NGC 2011b) members of the pair are found to be very similar. Kontizas et al. (1993) note that the core of NGC 2011a is elongated, so that another UV feature, which was named NGC 2011c, at an off-center position, but still in the dense core to be observed. The IUE spectra of NGC 2011b and NGC 2011c are found to be very similar.

Unfortunately, the second component, NGC 2011b, is not covered in the WFPC2 field presented here, but the elongation of the core of NGC 2011a is shown very well in these observations, and a part (if not all) of the third possible component, NGC 2011c, can be seen at the southern corner of the PC frame of the camera (Fig. 1, right). In this Letter we report the peculiar behavior of the main sequence of NGC 2011, and we discuss its relation to the multiple nature of the cluster.

2. OBSERVATIONS AND PHOTOMETRY

The results presented here are based on a single WFPC2 field taken with the PC frame centered on NGC 2011a. The data were taken in filters F555W (~V) and F814W (~I) as part of the program GO-8134, and we retrieved them from the HST data archive. The six data sets (archive names U5AY0801R-USAY0806R) include three exposures (2 × 350 and 1 × 10 s) for each filter. The data were reduced using the HSTphot photometry package (Dolphin 2000). A detailed account of the photometry process with HSTphot is given by Gouliermis et al. (2005).

We combined the two images of 350 s in each filter using the subroutine coadd to produce deep exposures. HSTphot is suited for HST WFPC2 observations, and it is especially designed to perform simultaneous photometry on both short- and long-exposure images and for more than one filter. We thus performed our photometry on both deep (700 s) and shallow (10 s) images observed in both filters to produce the final photometric catalog of 6760 stars found in the observed field. The detection limit of the short exposures is \( V \approx 21.5 \) mag, and the brightest magnitude observed in the long exposures is \( V \approx 18.5 \) mag. The present study is part of an ongoing inves-
3. STELLAR POPULATIONS IN THE OBSERVED FIELD

3.1. The Forklike Main Sequence

The color-magnitude diagram (CMD) of the stars found in the observed area of NGC 2011 is shown in Figure 2. In this CMD the upper main sequence is shown to have two distinct branches, one redder than the other, that form a forklike pattern. This feature is observed in the stellar samples from both short and long exposures. The obvious resemblance of these two main sequences suggest that they are populated by similar kinds of stars and that the shift of the one to the red is probably due to reddening. Indeed, as shown below, the right sequence (hereafter the “red” main sequence) seems to fit the same isochrone models as the left (“blue” main sequence) but assuming higher extinction.

In order to distinguish the areas where the stars of each of these sequences are located and to check for any difference in their spatial distributions, we selected two regions in the CMD, covering the bright stars that populate each of the sequences, and we constructed the corresponding stellar maps. We selected stars down to $V = 19$ mag, which is the faintest magnitude where the two sequences are discriminable. The map of both stellar groups is shown in Figure 3, where the stars of the blue main sequence (MS) are plotted with open circles and the red MS with filled circles. In this map the loci of the bright stars representative of each sequence can be easily distinguished. Specifically, the red MS is found to correspond to the main body of NGC 2011 (within ~0.4 from its center), observed in the PC frame of the WFPC2 (in addition to a loose strip of stars outward to the east/northeast), while the stars of the blue MS are located in the surrounding region, and they “avoid” the main cluster. This observation indicates that there is preferably higher extinction in the area of the cluster than in the surrounding region.
Indeed, as shown in Figure 1, NGC 2011 is located in a region of high nebulosity. This region belongs to a stellar aggregate, along with several stellar associations and other young clusters in the stellar supercomplex SC2. This complex, which is classified as an "active star-forming complex" (Livanou et al. 2006) is located at the southern edge of the supergiant shell LMC 4, the borders of which are characterized by recent star formation (e.g., Yamaguchi et al. 2001). An examination of the region of NGC 2011 in the Magellanic Cloud Emission Line Survey (MCELS; Smith et al. 2005) showed no trace of interstellar gas that has been heated and energized by stars. On the other hand, observations with Spitzer within the SAGE (Surveying the Agents of a Galaxy’s Evolution) survey (Meixner et al. 2005) show a prominent bright infrared source on the cluster itself, giving clear indications of recent star formation in the region of NGC 2011. Could it be that NGC 2011 is a cluster on the act of forming stars? The observations presented so far seem to support this idea.

3.2. Characterization of the Observed Stellar Populations

If we assume that each of the two branches of the bright forklike MS (blue and red) represents a stellar sample with a fully populated mass function (down to the detection limit), it would be interesting to see the whole CMD of each of these populations. Therefore, considering that each one of the areas, which covers stars of the blue and red main sequences, is well defined, the faint part of the corresponding CMD can easily be found if we select stars confined only in each of these areas. The PC frame is found to cover almost all of the brightest stars of the red MS, without any contamination by stars of the blue MS, and therefore we selected all stars found in the PC frame, as well as in the small strip outward from the cluster to the east/northeast direction (Fig. 3) to construct the corresponding CMD down to the detected faintest magnitudes. For the full magnitude range CMD, which corresponds to the blue MS, we selected two boxed areas, to the northeast and south of the PC frame, which are found to cover most of the bright young stars of the blue MS (Fig. 3).

Considering that the WFPC2 field of view (FOV) is too small to also cover a useful part of the general field of the LMC, and that the observed region is not representative of this field (Fig. 1), one cannot expect to have any good measurement of the contribution of the LMC field population to the observed CMDs. Nevertheless, we selected the two most distant corners of the observed FOV (one to the far east and one to the far north of the PC frame) for plotting an indicative CMD of the general LMC field. The CMDs of all three selected areas are shown in Figure 4. It can be seen that indeed the whole magnitude range of stars, which belong to the red and blue MSs, can be distinguished. This was further verified by applying isochrone fitting to each of the CMDs shown in Figure 4. The evolutionary models of the Padova group in the HST WFPC2 VEGA magnitude system (Girardi et al. 2002) were used.

We found that both blue and red MSs are young with an age not older than about 10$^7$ yr in agreement with the result of Elson & Fall (1988). Still there is a strong difference in reddening between the blue and red MSs. Specifically, we found that the CMD of the blue MS shows a modest color excess of $E(B-V)=0.01$ mag, equal to the one found for the field, while the color excess found from model fitting on the red MS CMD is almost an order of magnitude higher, $E(B-V)=0.15$ mag, which corresponds to optical extinction $A_V=0.48$, assuming the reddening law $R_V=3.2$ (Mihalas & Binney 1981). This result verifies the suggestion mentioned earlier, that although both MSs are populated by similar kinds of stars, there is a clear discrepancy in the extinction in each of the corresponding areas, indicating that the main body of NGC 2011 is embedded, strongly suggesting a recently formed star cluster, which did not have the time to expel its gas. Still, it should be noted that the suggested reddening for NGC 2011 is much higher than the one given by van den Bergh (1981), who presented integrated colors for 147 LMC clusters.

4. FINAL REMARKS

We showed evidence of the coexistence of two stellar groups in the same region of the LMC cluster NGC 2011, as it is observed with WFPC2. This is exhibited by a double pattern in the bright end of the observed main sequence. We found that each branch of this forklike feature represents a fully populated main sequence (down to the detection limit), showing indications of twin stellar populations, the one located in the cluster itself being still embedded in its star-forming gas. It is not clear if these two populations belong to a single stellar system or not, but in any case, the results presented so far raise interesting questions concerning the relation between the peculiar mass sequence of NGC 2011 and its binary nature. Considering that the data presented here are the best available today of this cluster, with no kinematic information on individual stars in the region, we can only speculate on the scenarios that explain our observations.

The simplest explanation would be that both main sequences belong to the cluster itself, but some of the stars are not obscured by nebulosity, which is concentrated in the core of NGC 2011. But in order to explain the existence of massive stars away from the core, since dynamical evolution would tend to segregate these stars to the center (Meylan & Heggie 1997), one should assume that the cluster is under disruption. Indeed, the elongated core observed in our WFPC2 field supports this idea. Furthermore, the surface density profiles constructed for NGC 2011 within our study of mass segregation (S. Lianou et
al. 2006, in preparation) deviate from King (1962) profiles, indicative of tidal stripping, although King models may not be the most suitable for such clusters, which are not tidally truncated (Elson et al. 1987). Still, NGC 2011 is a binary cluster with indications of tidal interaction from the companion cluster NGC 2011b (Kontizas et al. 1993), and with a third component observed in our WFPC2 data, as a stellar “bridge” between NGC 2011a and NGC 2011b (Fig. 1).

Under these circumstances, and since the stellar populations of both members of the binary cluster are identical, one may ask if the stars in the blue MS are not members of NGC 2011a but rather of the second companion, NGC 2011b, stripped away from their host through dynamical interaction with the primary. According to recent N-body simulations, clusters with an initial separation smaller than 60 Myr due to loss of angular momentum from escaping stars (Portegies Zwart & Rusli 2006). Considering that the actual center-to-

center separation of the NGC 2011 pair is 0.95 (Kontizas et al. 1993), this is a possible future for this system. Are the two members of the NGC 2011 binary cluster very young clusters in the process of early dynamical merging? It is probable, but more observations preferably with the wider FOV of WFC of the Advanced Camera for Surveys on HST will definitely give us a more clear-cut answer.

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