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A near-ultraviolet view of the inner region of M 31 with the large binocular telescope *(Research Note)*

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ABSTRACT

Aims. We present a 900 s, wide-field *U* image of the inner region of the Andromeda galaxy obtained during the commissioning of the blue channel of the Large Binocular Camera mounted on the prime focus of the Large Binocular Telescope.
Methods. Relative photometry and absolute astrometry of individual sources in the image was obtained along with morphological parameters aimed at discriminating between stars and extended sources, e.g. globular clusters.
Results. The image unveils the near-ultraviolet view of the inner ring of star formation recently discovered in the infrared by the Spitzer Space Telescope and shows in great detail the fine structure of the dust lanes associated with the galaxy inner spiral arms. The capabilities of the blue channel of the Large Binocular Camera at the Large Binocular Telescope (LBC-Blue) are probed by direct comparison with ultraviolet GALEX observations of the same region in M 31. We discovered 6 new candidate stellar clusters in this high-background region of M 31. We also recovered 62 *bona-fide* globulars and 62 previously known candidates from the Revised Bologna Catalogue of the M 31 globular clusters, and firmly established the extended nature of 19 of them.

Key words. galaxies: individual: M 31 – globular clusters: general

1. Introduction

As the nearest giant spiral galaxy, Andromeda (M 31) provides a unique opportunity to study the structure and evolution of a massive twin galaxy of the Milky Way (MW) from the "outside", and, by comparison with the MW, to address the question of variety in the evolutionary histories of massive spirals. In particular, the M 31 Globular Cluster (GC) system provides the crucial bridge to connect the integrated-light-based methods that are used to study GCs in distant galaxies to the resolved-star-based methods that can be applied to the MW clusters (see e.g. Galleti et al. 2004, 2006a, hereafter G04, G06a).

Hierarchical structure formation models predict that the halo of a large galaxy is assembled through mergers of smaller subsystems. It has been suggested that M 31 originated as an early merger of two or more relatively massive metal-rich progenitors (van den Bergh 2000, 2006). The prominent tidal stream in M 31 (Ibata et al. 2001) extending several degrees from the centre of the galaxy (McConnachie et al. 2003), and the newly discovered arc-like over-density connecting M 31 to its dwarf elliptical companion NGC 205 (McConnachie et al. 2004), are indeed the most spectacular interaction signatures presently known in the Local Group (LG) among the few nearby examples of tidal debris trails from galaxies currently merging.

The M 31 outer disk is warped, and the halo contains numerous loops and ripples. Moreover, infrared photometry of the disk by IRAS (Habing et al. 1984) and by the Spitzer Space Telescope has revealed two rings of star formation off-centred from the galaxy nucleus (Gordon et al. 2006). The two rings appear to be density waves propagating in the disk. Numerical simulations show that both rings may result from a companion galaxy plunging head-on through the centre of the M 31 disk about 210 Myr ago (Block et al. 2006). The Galaxy Evolution Explorer (GALEX, Thilker et al. 2005) obtained far (1350–1750 Å, FUV) and near (1750–2750 Å, NUV) ultraviolet mosaic imaging of the M 31 nucleus at a spatial resolution of 5″ in NUV. The M 31 inner ring region is not well detected by GALEX. The Large Binocular Telescope (LBT), a forefront observational facility built and operated by an Italian-German-American collaboration, is at present the only telescope capable to unveil the near UV counterpart of the Spitzer inner ring in M 31, thanks to the optimal combination of telescope size, spatial resolution (a factor 5 higher than in GALEX), field of view and sensitivity in the blue bands. The LBT is located on Mount Graham, Arizona, and in its final configuration will have two

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8.4 m primary mirrors on a common mount, feeding various instruments (Salinari 1999; Hill et al. 2006). Science commissioning at prime focus was carried out during October–December 2006 with a single mirror feeding the blue channel of the Large Binocular Camera (LBC-Blue; Ragazzoni et al. 2006; Giallongo et al. 2007), a UV-optimized wide-field mosaic camera consisting of four CCD chips of 2048 × 4608 pixels, with a mean pixel scale of 0.225″/pixel. The mosaic covers a field of view (FOV) of 24′ × 25′; once the inter-chip gaps are taken into account, the effective sampled area is ∼23′ × 23′.

In this paper we present results from a 900 s wide-field U band image of the M 31 inner regions, reaching the limiting magnitude $U \sim 25$ mag. This image was obtained with the LBT during the commissioning phase, with the purpose of testing the U capabilities of the blue channel of the LBC. The image is compared to the GALEX and Spitzer views of the same area. Results are also presented on new M 31 candidate stellar clusters that were identified on the image.

2. Observations and data analysis

The $t_{\rm exp}$ = 900 s U (Bessel) image of M 31 that is the subject of the present analysis was acquired on UT 2006, December 25, with the LBT telescope set at RA(J2000) = 00 42 42.8 and Dec(J2000) = +41 16 12.8. The selected field is centred on the M 31 inner dust ring discovered by Spitzer at about 0.5 kpc from the M 31 centre. The inner ring extends for about 9′ in the Spitzer image. The field of view of LBC-Blue allows to cover it entirely and to sample also small portions of the M 31 outer ring. Seeing conditions during the observations were modest ($FWHM \simeq 2''$ at 1.4 air-masses). Nevertheless, we obtained an outstanding image of M 31, and fully succeeded both in tracing the fine structure of the innermost regions of Andromeda and finding new candidate stellar clusters in the galaxy.

The image was bias-subtracted and flatfield-corrected using standard IRAF[1]/mscred procedures and best flat-field and bias images kindly made available by the LBC team[2]. Each chip was then searched for sources down to 3σ above the local background level using Source Extractor (Sextractor, Bertin et al. 1996). Sextractor provides positions and magnitudes as well as a number of morphological parameters of the detected sources that can be used for source classification, e.g. to discriminate between Point Sources (PS) and Extended Sources (ES, see below). Our final list of well behaved sources contains 5539 entries selected to have Sextractor quality flag equal to 0, that means optimally measured sources.

Astrometric catalogues typically used to search for counterparts and find astrometric solutions such as the GSC2 or the 2MASS have very few stars in this innermost region of M 31. Fortunately, a very appropriate secondary source is the Johnson-Kron-Cousins UBVRI photometry down to $V \sim U \sim 23$ mag of 371781 sources in a 2.2 deg^2 area of M 31 by Massey et al. (2006, hereafter M06). Our field is fully included within the area covered by M06. M06 data-set contains stars as bright as $V \sim 14$ mag, that allow to obtain absolute astrometric solutions using standards from the USNO-B1.0 catalogue (Monet et al. 2003). We found more than a thousand stars in common with M06 in each chip of our image. With these stars we derived astrometric solutions modelled by third order polynomials with residuals ≤0.16″ rms in both RA and Dec. The astrometric solution was then ingested into the mosaic image and a background subtracted version was produced using SWARP[3] (Bertin et al. 2002). This image is shown in the upper panel of Fig. 1. We advise the reader that the electronic version of the figure should be retrieved to appreciate the incredible amount of information that is present in this image.

The stars in common with M06 also allowed us to derive a rough absolute photometric calibration of the sources in our image. Since we lack colours we cannot apply colour-terms to our calibration, thus the uncertainty in our absolute photometry is of the order of ±0.5 mag, very large but still sufficient to provide a rough estimate of the limiting magnitude we have reached. From 596 relatively bright ($U \lesssim 20$ mag) stars in common between the two catalogues we found $U = MAG\_AUTO + 25.63$ mag, where *MAG_AUTO* are the instrumental magnitudes we obtained from Sextractor and U are the calibrated magnitudes in the standard system from M06. The faintest sources in our catalogue have $U \simeq 25$ mag, 90% of the sources have $U \lesssim 22$ mag . The uncertainty in the relative photometry for $U \lesssim 22.0$ mag is $\epsilon_U \lesssim 0.05$ mag, for $U \lesssim 24.0$ mag is $\epsilon_U \lesssim 0.10$ mag. This is perhaps the deepest wide-field, high resolution U image of Andromeda ever obtained.

3. Mapping the M 31 dust lanes: LBC vs. GALEX and Spitzer

The LBT image (see upper panel in Fig. 1) shows in great detail the fine structure of the dust lanes associated with the M 31 inner spiral arms and provides a superb demonstration of the outstanding capabilities of the LBC-Blue system, in a regime of high and strongly varying background such as the considered portion of Andromeda, where the very luminous and extended bulge is superposed to the inner pattern of the spiral arms, traced by bright stars and prominent dust lanes. In Fig. 1 we show the LBC-Blue mosaic compared to a mosaic ∼24′ × 25′ image of the M 31 nucleus obtained by GALEX (lower-left panel; Thilker et al. 2005) and with an Infrared (24 μm) image (Gordon et al. 2006) of the Andromeda galaxy observed with the Multiband Imaging Photometer (MIPS; lower-right panel) on board to the Spitzer telescope[4].

The M 31 outer ring at a radius of 10 kpc is clearly visible in the three images, while the inner ring is not resolved by the GALEX data, which only show diffuse light at its position. Indeed, the simple visual comparison of the LBC-Blue and the GALEX images allows one to appreciate the striking resolution capabilities of the blue camera on LBT. The structures of the M 31 arms that appear smeared and undefined in the GALEX image, are resolved into individual stars by the LBC-Blue camera. The LBC-Blue image sharply outlines the contours of the M 31 inner emitting regions that appear sparse and diffuse on the GALEX image.

The LBC-Blue and the Spitzer images are almost the positive and negative of each other, since at the infrared wavelengths sampled by Spitzer, dust is the main light emitter, while in our U image we can see dust structures only because they intercept the light coming from the disc and bulge of M 31 lying in the background. Hence, any dust lane or feature that is apparent in Spitzer images and is not seen in the LBC U image is probably

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[2] `http://lbc.oa-roma.inaf.it/`

[3] See `www.terapix.fr`

[4] The image was retrieved from the NASA web site at `http://ipac.jpl.nasa.gov/media_images/ssc2005-20a1.jpg`

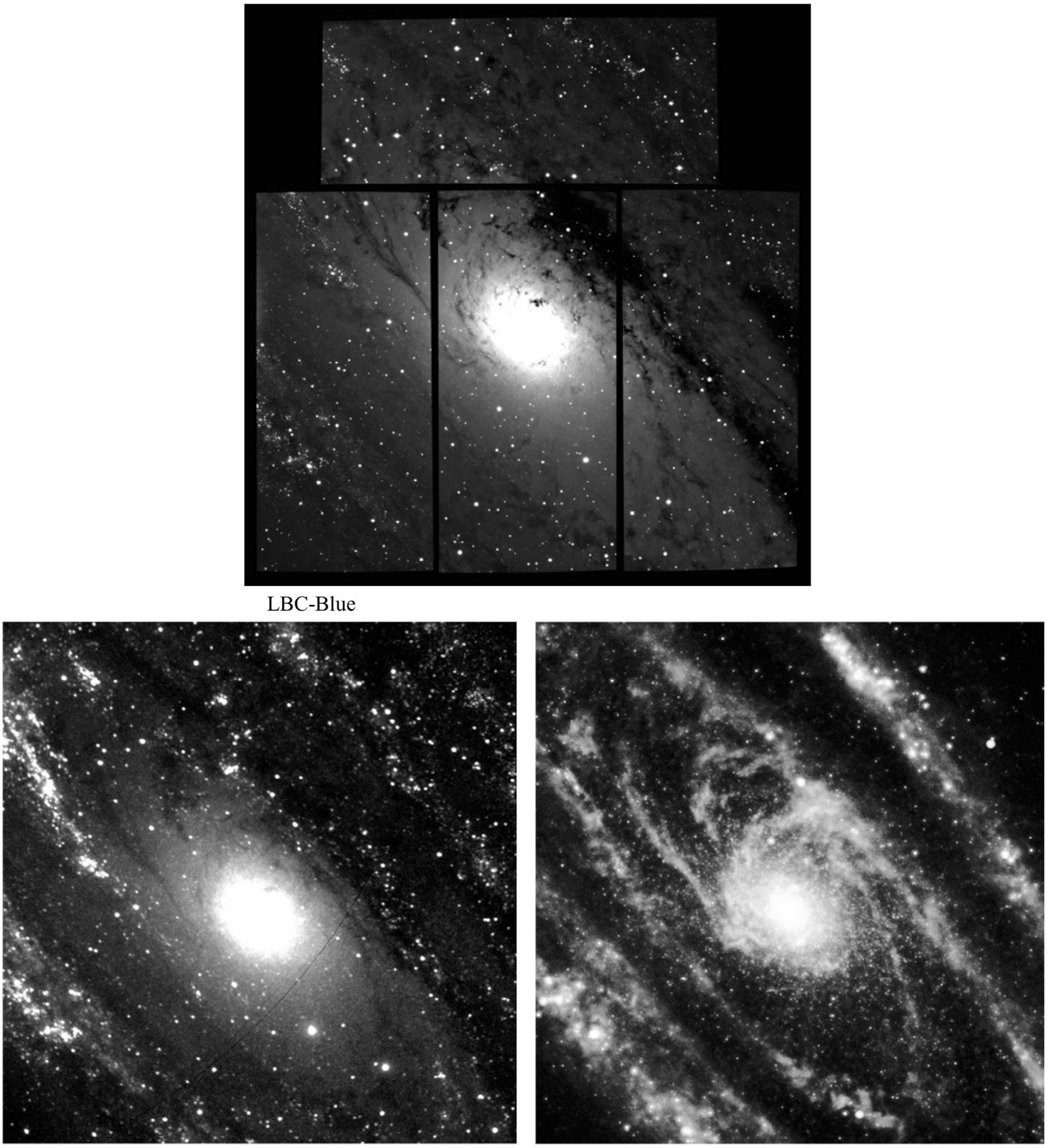

Fig. 1. *Upper panel*: sky-subtracted mosaic image of the center of M 31 obtained with the LBC-Blue. *Lower-left panel*: the Andromeda galaxy observed with GALEX (from Thilker et al. 2005). The image is a composite representation of the GALEX FUV and NUV data. Field of View is $\sim 24' \times 25'$, North is up and East is left. The M 31 outer ring at a radius of 10 kpc is clearly visible in both images, instead the inner ring is not resolved by the GALEX data, which only show diffuse light at its position. *Lower-right panel*: the same portion of Andromeda observed with the Multiband Imaging Photometer (MIPS) on board to the Spitzer Space Telescope at a wavelength of 24 microns (from Gordon et al. 2006). Two well defined dust rings are clearly visible, an outer ring at a radius of 10 kpc, and a second 1.5 by 1 kpc inner ring offset by approximately 0.5 kpc from the galaxy nucleus. Dimensions and orientation of the GALEX and Spitzer images are the same as in the LBC image.

located *behind* most of the stellar disc of M 31 in that direction. This comparison allows some insight on the three-dimensional structure of the dust patterns in M 31. On the other hand, a dust lane that is discerned on the LBC image but is not seen in the Mid IR image may indicate that the feature has a different temperature than the other structures. Moreover the finest details of the dust lanes and annuli can be discerned on the LBT image at a higher level of resolution than in the Spitzer image (Gordon et al. 2006).

A deeper discussion of these aspects is beyond the scope of the present paper, and here we simply draw the attention on another rather straightforward use of the LBT image: a search for new candidate stellar clusters in M 31.

4. New candidate stellar clusters

Since the review by Harris & Racine (1979), there has been a longstanding debate in the literature about the so called "missing candidate" globular clusters in the bulge of M 31 (see e.g. Barmby et al. 2001; Puzia et al. 2005, and references therein, for recent discussions of this problem). We have used our LBT *U* image to search for new globular clusters in the inner regions of M 31, altough the *U* filter is far from being the ideal passband to search for classical old (and hence red) GCs. In fact, our U image is best suited for the detection of young/hot stellar populations. Therefore it is likely that any new cluster identified in this image is a young system, either an open cluster or a blue luminous compact cluster (BLCC) as recently found by Fusi Pecci et al. (2005).

The long experience in the search for GCs in M 31 taught us that the lists of GC candidates are mainly contaminated by foreground Galactic stars and distant galaxies lying in the background, while HII regions and other types of spurious sources play a secondary role, (see G04 and G06a). Lacking high spatial resolution allowing to resolve clusters into individual stars (see Barmby et al. 2007; Galleti et al. 2006b, 2007), the usual way to disentangle GCs from background galaxies is via low resolution spectroscopy allowing the measure of the source's radial velocity: distant galaxies have high positive velocities due to cosmological recession, while *bona-fide* M 31 GCs should have velocities comparable to the galaxy systemic velocity, (V_r(M 31) $\simeq -300 \pm 450$ km s^{-1}, G06a). For those cases where the actual nature of a candidate cannot be discerned by the radial velocity, a crucial test is to check whether the target appears on the image as ES (hence a genuine cluster) or as a PS (i.e. a star, see G06a). In the Revised Bologna Catalogue of the M 31 globular clusters (RBC, G04) we keep track not only of confirmed *genuine* GCs and of candidates yet to be confirmed, but also list *false* candidates that turned out to be galaxies, stars and HII regions.

The high surface brightness background and the strong extinction of the prominent dust structures in our LBT image proved a natural and very efficient shield against contamination by background galaxies. Among the 124 spurious sources flagged as confirmed galaxies in the RBC, only one occurs in the region sampled by our image. Moreover, the *U* passband also disfavours contaminating background galaxies, which are typically quite red (G04, G06a). Hence any "roundish" source in our image that appears to be significantly more extended than a star of similar luminosity may be a good stellar cluster candidate.

To search for new candidates we first cross-correlated our catalogue against the RBC (which now includes also the clusters and candidates recently found by Kim et al. 2007), using a tolerance radius of 1″. In this way we recovered 62 confirmed clusters, 27 confirmed stars, and 62 candidate clusters.

92% of the M 31 confirmed GCs recovered in our LBT image have *U* magnitude brighter than 20 mag, hence about 5 magnitudes brighter than the limiting magnitude of our photometry ($U \sim 25$ mag). Then, we plotted all sources in a diagnostic diagram where the log of the isophotal area is displayed against the log of the isophotal flux (log *A*–log *F* diagram, hereafter AF diagram, see G06a). This diagram is produced out of quantities directly output by Sextractor and is very effective in discriminating between PSs and ESs (see G06a).

The AF diagram of the sources (small dots) in our LBT image is shown in Fig. 2, with confirmed GCs plotted as pentagons,

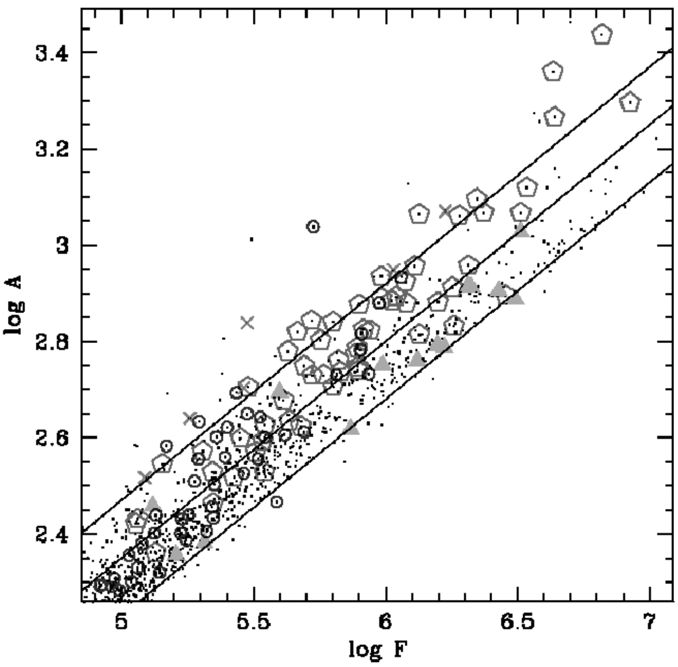

Fig. 2. *F-A* diagram for the detected sources (dots). Pentagons are confirmed globular clusters, filled triangles are confirmed stars, and small open circles are the previously known candidate globular clusters from the RBC. Crosses are our new candidate clusters.

previously known *candidate* GCs as encircled dots, and the previously known (from the RBC) stars as filled triangles. The AF diagram is usually dominated by a relatively narrow, well defined diagonal band with a sharp lower envelope due to PSs (stars). Sources lying significantly above the PS sequence are clearly extended (they have a larger isophotal area for their flux with respect to a star). The poor seeing conditions of our observations resulted into a rather wide PS strip, as judged by the position of known stars in the AF diagram. However, adopting a very conservative threshold and selecting as bona-fide ESs only sources lying above the upper diagonal line running parallel to the PS band of Fig. 2, we were able to identify 25 previously unknown Extended Sources. Visual inspection of the image revealed that most of these new ESs appear somehow irregular or superposed to strong structures of the background and/or have ellipticity $e > 0.4$ (see Barmby et al. 2007; and Galleti et al. 2007), or have some other problem making their classification uncertain. Notice that the shape of each new ES was locally compared to that of surrounding confirmed stars in order to exclude elongation effects due to worse focus or astigmatism in some parts of the field.

To be conservative, we excluded all the uncertain sources, and were thus left with *six* well behaved, nearly round sources displaying a clear halo of light surrounding the central peak, as it is typical of genuine stellar clusters. Stamp size images of these six new good stellar cluster candidates are shown in Fig. 3 along with one previously known genuine M 31 GC and one star of similar magnitude, for comparison. The newly identified cluster candidates have $17.5 \lesssim U \lesssim 19.5$ mag; they have been named according to the RBC convention, as they will be included in the updated catalogue; their main characteristics are summarised in Table 1. Notice that, by comparing the *U* magnitudes of the new candidates with the values by M06, we found differences in the range from 0.3 mag for the brightest candidates up to 2.8 mag for the faintest ones, with our measurements being systematically

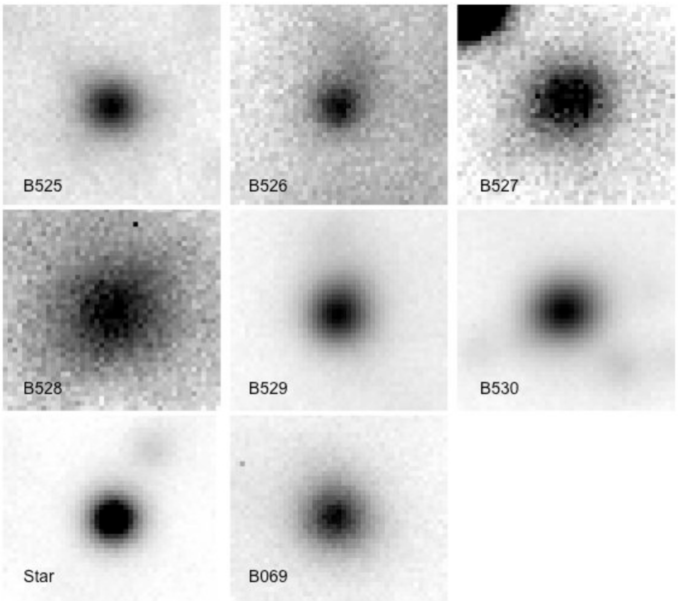

Fig. 3. U images of the six new candidate clusters, a star ($U \sim 18.5$ mag) and a confirmed globular cluster with $U \sim 18.8$ mag (B069). Notice that B069 is one of the blue luminous compact clusters (BLCCs) recently found by Fusi Pecci et al. (2005). Each image is $\sim 10''$ on a side.

Table 1. Newly discovered candidate stellar clusters.

Name	RA_{J2000}	Dec_{J2000}	U^a	$FWHM$	R
B525	00:41:45.24	41:12:29.38	18.75	2.5″	1.22
B526	00:42:03.08	41:16:23.50	18.90	4.1″	1.98
B527	00:42:10.93	41:29:59.02	19.36	4.3″	2.05
B528	00:43:11.90	41:23:47.91	19.25	5.4″	2.54
B529	00:42:12.07	41:25:38.66	18.15	2.6″	1.22
B530	00:42:50.31	41:25:12.70	17.72	2.8″	1.33

[a] Approximate values, see text.

brighter. The reason is that we measured magnitudes of the extended sources by using isophotal fluxes, while M06 measured magnitudes by PSF fitting modelled on suitable PSF stars, thus probably losing light for the most extended sources.

To further investigate the nature of the new cluster candidates we checked the HST archive and found that B528 and B530 have counterparts on ACS@HST archival images. B528 appears on three ACS images, namely: an $F435W$ 2200 s long exposure (Program 10006, PI Garcia), and on two 2370 s long exposures in the $F606W$ and $F814W$ filters (Program 10260, PI Harris). On the $F435W$ image the cluster appears as a young low-density association (probably an open cluster), that becomes progressively fainter on the $F606W$ and $F814W$ images, respectively. On the same frames we also identified two confirmed GCs, B162 and B159, which are bright and well defined on the ACS images while appear rather faint on the U LBC-Blue image. B530 appears on an $F606W$ and an $F814W$ WFPC2 3200 s image (Program 5971, PI Griffiths). In all the WFPC2 images the object appears as an extremely loose ensemble of stars.

We also computed the R parameter (i.e. the ratio of the $FWHM$ of a given source over the average $FWHM$ of stars in the same image, G06a), where $R \gg 1.0$ values indicate the extended nature of the source. Out of the 62 RBC candidate GCs found in our image, 19 are found to have $R > 1.20$, thus establishing their extended nature on a quantitative basis. Their names

Table 2. R parameter for candidate M 31 GCs from the RBC.

Name	R	Name	R	Name	R
B079	2.113	B177	1.236	B095D	1.206
B080	1.590	B269	1.364	B097D	1.480
B108	1.277	B271	1.864	AU008	2.382
B142	1.332	B057D	1.353	V234	1.449
B150	1.327	B072D	1.279	M001	1.225
B157	1.231	B089D	1.273		
B172	1.230	B092D	1.873		

and R ratios are provided in Table 2. With this additional piece of information, any radial velocity estimate will suffice to confirm whether they are genuine M 31 GCs or not.

5. Discussion and conclusions

The results presented in this paper provide first quantitative hints of the outstanding potential of the blue channel of the LBC on the Large Binocular Telescope. In spite of rather poor seeing conditions, a very deep U image of M 31 was obtained, reaching $U \simeq 25.0$ mag and revealing a harvest of details of the central region of Andromeda. Using a secondary astrometric catalogue it was possible to derive a more than satisfactory global astrometric solution (rms $\simeq 0.16''$). Though the background in the sampled region is very high and strongly variable we were able to obtain relative photometry accurate to ± 0.1 mag over the magnitude range $16.5 \lesssim U \lesssim 24.0$ mag. Scientific return was easily obtained even from these very first commissioning images: (a) we highlighted fine structure details of the dust lanes in the inner regions of M 31; (b) six new good-quality M 31 stellar cluster candidates were identified, to be followed up spectroscopically; (c) the extended nature of 19 previously known GC candidates was also established on firm quantitative basis.

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