



Extended star clusters in NGC 1023 from *HST*/ACS mosaic imaging

Duncan A. Forbes,¹★ Andres Almeida,² Lee R. Spitler^{3,4} and Vincenzo Pota¹

¹Centre for Astrophysics and Supercomputing, Swinburne University, Hawthorn, VIC 3122, Australia

²Departamento de Ciencias Físicas, Universidad Andres Bello, Republica 220, Santiago, Chile

³Department of Physics and Astronomy, Faculty of Sciences, Macquarie University, Sydney, NSW 2109, Australia

⁴Australian Astronomical Observatory, PO Box 296 Epping, NSW 1710, Australia

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ABSTRACT

Faint fuzzies (FFs) are a relatively new class of star cluster, first found in the nearby S0 galaxy NGC 1023 by Larsen & Brodie using Wide Field Planetary Camera 2 (WFPC2) images from the *Hubble Space Telescope* (*HST*). Here, we investigate the star cluster system of NGC 1023 using an eight pointing mosaic of Advanced Camera for Surveys (ACS) images from *HST*. We identify blue and red normal globular clusters (two of which are particularly luminous and dense) and two ultracompact dwarf objects (with effective radius ~ 10 pc). With our more complete spatial coverage, we also find 81 red and 27 blue FFs. We confirm the association of the red FFs with the disc of NGC 1023, consistent with them being long-lived open clusters. Half of the blue FFs appear to be associated with the dwarf satellite galaxy NGC 1023A (which was largely absent from the original *HST*/WFPC2 coverage), while the remainder are spatially coincident with the densest H I gas that surrounds NGC 1023. The blue FFs have colours that are consistent with young (few 100 Myr old) star clusters that formed during the most recent interaction between NGC 1023 and its satellite NGC 1023A.

Key words: galaxies: evolution – galaxies individual: NGC 1023 – galaxies: star clusters: general.

1 INTRODUCTION

At the turn of century, Larsen & Brodie (2000) reported the discovery of star clusters in the nearby (11.1 Mpc) S0 galaxy NGC 1023 using *Hubble Space Telescope*/Wide Field Planetary Camera 2 (*HST*/WFPC2) imaging. As well as normal globular clusters (GCs; see Kartha et al. 2014 for a recent analysis), NGC 1023 hosts a population of faint objects with large sizes (i.e. effective radii of 7–20 pc) and low surface brightness. Most are red in colour and subsequent follow-up spectroscopy with the Keck telescope confirmed their high metallicity and old ages (Larsen & Brodie 2002). They dubbed these objects faint fuzzies (FFs). They add to the ever increasingly family of old star clusters which are filling the parameter space of size and luminosity (e.g. Brodie et al. 2011; Brüns & Kroupa 2012; Forbes et al. 2013).

Using the Advanced Camera for Surveys (ACS) Virgo Cluster Survey (VCS) survey data, Peng et al. (2006) found a number of similar objects in 12 early-type Virgo cluster galaxies (most of which were morphologically classified as S0). They suggested that the best Galactic analogue to these clusters, which they called Diffuse Star Clusters (DSCs), were old open clusters.

Based on the kinematics of red FFs in NGC 1023, Burkert, Brodie & Larsen (2005) found them to lie in a fast rotating ring structure and suggested that they had formed in a galaxy interaction. Chies-Santos

et al. (2013) compared red FF kinematics with those of planetary nebulae and the H I gas finding disc-like kinematics and concluded that the red FFs are not associated with an ongoing galaxy merger but are simply long-lived open disc clusters. Further support for the long-lived *in situ* formation of the FFs comes from the modelling of Brüns, Kroupa & Fellhauer (2009) who showed that merging star clusters could reproduce well the size, mass and spatial distribution of FFs in NGC 1023.

Thus, FFs and DSCs appear to be old open clusters associated with discs in lenticular galaxies. They may also be common in the discs of late-type spirals but are difficult to detect (and therefore study) within a complex, dusty disc.

Here, we analyse a mosaic of eight *HST*/ACS images in two filters of NGC 1023. This is one of only a few early-type galaxies with such extensive ACS spatial coverage. It also includes the dwarf satellite galaxy NGC 1023A, which was largely missing from the *HST*/WFPC2 coverage. With a wider and more continuous field of view than the original study of Larsen & Brodie (2000) using *HST*/WFPC2, we search for additional red FFs to confirm their disc-like 2D distribution. Larsen & Brodie (2000) also found two blue FFs associated with NGC 1023A. Greater spatial coverage will also aid in quantifying the blue FF population.

2 DATA REDUCTION AND ANALYSIS

The eight *HST*/ACS *F475W* (*g*) and *F850LP* (*z*) band images used in this study were taken as part of proposal 12202 (PI: Sivakoff).

★E-mail: dforbes@swin.edu.au

Table 1. Star clusters in NGC 1023. See the online version for full table.

ID	RA (J2000)	Dec. (J2000)	g (mag)	g_{err} (mag)	z (mag)	z_{err} (mag)	$g - z$ (mag)	$g - z_{\text{err}}$ (mag)	R_e (pc)	R_{err} (pc)	R_{err} (pc)
137	40.0883	39.0554	24.199	0.090	22.952	0.109	1.246	0.141	0.37	1.01	-0.37
138	40.1050	39.0574	23.087	0.048	22.125	0.072	0.961	0.086	0.39	0.79	-0.32
139	40.1041	39.0668	22.687	0.073	21.462	0.100	1.224	0.124	0.40	0.35	-0.40
...

Notes. Star cluster ID, coordinates, g mag and error, z mag and error, $g - z$ colour and error, effective radius and errors.

Exposure times were typically 768 s in the g band and 1308 s in the z band. The eight images create a rare ACS mosaic of a nearby early-type galaxy, covering approximately 12×7 arcmin².

Objects were detected in the individual images using the SExtractor package (Bertin & Arnouts 1996). Photometry of these sources was carried out using DAOPHOT. After the initial selection, magnitudes in 5 pixel (0.25 arcsec) radius aperture were measured and an aperture correction applied based on isolated objects in each image. Like the previous work of Larsen & Brodie (2000), our magnitudes may be systematically underestimated by a few tens of a magnitude for the largest objects but the colours are largely independent of any aperture correction. Total instrumental magnitudes were calibrated to the AB photometric system using zero-points of Sirianni et al. (2005). Effective radii (which we refer to as R_e or simply size) were measured using the ISHAPE code (Larsen 1999) with a King profile concentration parameter fixed to 30 (as is commonly used, e.g. Larsen & Brodie 2000; Usher et al. 2013). Thus, R_e is the half-light radius of the best-fitting $c = 30$ King profile. Common objects found in multiple pointings have their magnitudes and errors averaged. Finally, we correct the magnitudes and colours for Galactic extinction following Schlafly & Finkbeiner (2011). Below, we quote extinction-corrected values.

Star cluster candidates are selected to have colours $0.6 < g - z < 1.8$ (which correspond to $-2.6 < [Z/H] < 1.1$ according to the GC based transformation of Usher et al. 2012).

We also impose a faint magnitude cut of $z < 23.5$, which is effectively a cut in photometric error of less than ± 0.1 . In addition, a minimum size of 0.3 pc was used to effectively remove stars. We did not employ a maximum size limit but a visual inspection was carried out to conservatively remove background galaxies. Table 1 lists the positions, g and z magnitudes, $g - z$ colours and half-light effective radii for the final 358 star cluster candidates. This includes a dozen objects that may be associated with NGC 1023A.

3 RESULTS AND DISCUSSION

After applying the selection criteria described above, we show in Fig. 1 the z magnitude, $g - z$ colour and effective radius in parsecs (assuming the objects are associated with NGC 1023, i.e. at a distance of 11.1 Mpc).

The size–magnitude diagram shows a locus of objects with $R_e \sim 3$ pc – these are GC candidates. They include two bright objects (IDs 33 and 269 with $z \sim 18.5$, $M_z \sim -11.73$) that therefore have relatively high surface densities. In the case of object 269, it has a size of $R_e = 4.1$ pc and appears quite elongated. Both have spectra previously obtained from the Keck telescope (Cortesi et al. in preparation) confirming their association with NGC 1023, thus they appear to be very luminous GCs. The object 269 has been studied in detail by Larsen (2001) from *HST*/WFPC2 data. He measures the same size as we do and quotes an ellipticity of 0.37. He notes

that it is somewhat more compact than Omega Cen in the Milky Way but similar in density to G1 in M31. The similarities with Omega Cen and G1 suggest that 33 and 269 may both be the compact nuclei of a stripped dwarf galaxy. We also note two relatively bright objects (IDs 102 and 315 with $z \sim 20.3$, $M_z \sim -9.7$) with large sizes ($R_e \sim 10$ pc) that resemble low-luminosity ultracompact dwarfs (UCDs; see Forbes et al. 2013). The blue UCD ($g - z = 0.99$; ID: 102) has been confirmed with Keck spectroscopy (Cortesi et al., in preparation) to be associated with NGC 1023. At faint magnitudes ($z > 21.5$) a number of objects have sizes > 7 pc, i.e. FFs by the definition of Larsen & Brodie (2000). Using this selection, we find 109 FF candidates, 16 of which are in common with the original WFPC2 V and I band study of Larsen & Brodie (2000). Larsen & Brodie found that the red FFs do not have the standard Gaussian-luminosity function of GCs, but rather continued to grow in number down to their magnitude limit of $V \sim 24$. We find a similar behaviour for both the red and blue FFs. From the study of a large sample of extended clusters ($R_e > 10$ pc), Brüns & Kroupa (2012) found that the peak or turnover magnitude in early-type (i.e. both elliptical and lenticular) galaxies occurred around $M_V \sim -6.4$. If FFs have a similar turnover magnitude (i.e. $V \sim 23.8$ at the distance of NGC 1023), then our data have reached the peak of the luminosity function of the FFs.

In the colour–magnitude diagram, one can see the clear bimodality of the two GC subpopulations, and at fainter magnitudes the FF candidates. A simple colour cut between the blue and red GC subpopulations at $g - z = 1.15$ is assigned. This corresponds to $[Z/H] \sim -0.6$ (Usher et al. 2012), and hence $[\text{Fe}/\text{H}] \sim -0.9$. With this colour cut we find 81 red FFs and 27 blue FF candidates (including 2 previously identified by Larsen & Brodie 2000). This diagram also shows the location of the two UCDs and the two high-density GCs with intermediate colours.

The third panel shows the size–colour distribution. The FFs lie above the GCs in this panel with a similar distribution in $g - z$ colour (although the colour cut for the FFs could be redder by 0.05 mag than for the GCs). Red FFs clearly outnumber the blue FFs (81 versus 27). Here, we have followed the size cut of Larsen & Brodie (2000), i.e. at 7 pc. However, our selected star clusters hint at three size regimes, i.e. normal GCs with $R_e \sim 3$ pc, objects with sizes $3 < R_e < 12$ pc, and those with $R_e > 12$ pc (for the blue objects this may be $R_e > 14$ pc). Larger numbers of objects are needed to verify if this visual impression represents different types of star cluster.

In Fig. 2, we show the *HST*/ACS mosaic of NGC 1023, with the location of the blue and red FFs, the two UCDs and the H I gas distribution (from Morganti et al. 2006). Confirming previous works, the red FFs have a distribution similar to that of the underlying stellar disc. The blue FFs do not follow the disc of NGC 1023. About half of them lie near NGC 1023A, while most of the others are coincident with the densest H I gas.

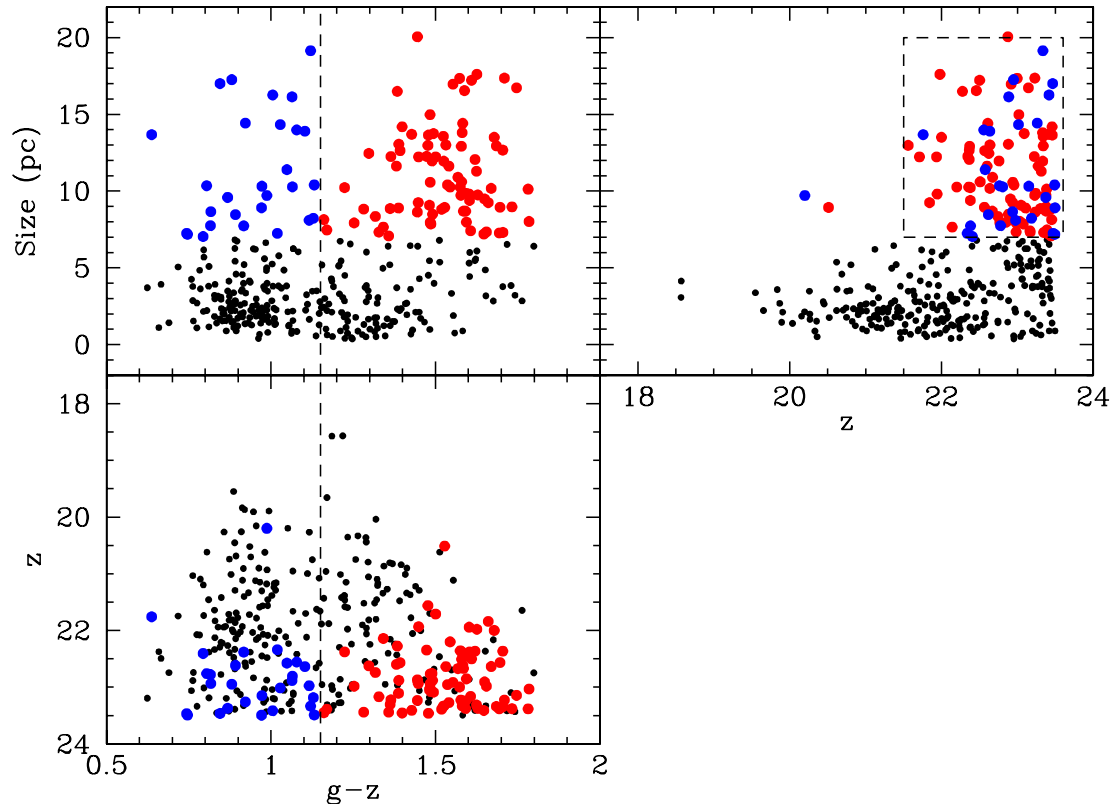


Figure 1. Star cluster candidates in NGC 1023. In all panels, objects with sizes effective radii $R_e > 7$ pc are shown by larger symbols and colour-coded blue/red. Top right: size in parsecs versus z magnitude. Note two bright ($z \sim 18.5$) compact GCs and two UCDs objects (size ~ 10 pc and $z \sim 20.5$). A box shows the selection criteria for FFs, i.e. $R_e > 7$ pc and $21.5 < z < 23.5$. Normal GCs have $R_e \sim 3$ pc. Top left: size versus $g - z$ colour. FFs are divided into blue and red FFs at $g - z = 1.15$. Lower left: colour–magnitude diagram. Two bright ($z \sim 18.5$) GCs are clearly visible with intermediate $g - z$ colours.

By fitting a simple model (i.e. equation 5 of Kartha et al. 2014) for both the average ellipticity and position angle (PA) simultaneously to the spatial distribution of red FFs, we find $PA = 82 \pm 3^\circ$ and $b/a = 0.4 \pm 0.2$. The stellar disc of NGC 1023 has an ellipticity of $b/a = 0.26$ and $PA \sim 85^\circ$ from a disc–bulge decomposition by Cortesi et al. (2013). This supports the impression by eye in Fig. 2, and confirms the findings of Larsen & Brodie (2000), that red FFs are indeed associated with the disc of NGC 1023. In Fig. 3, we show the azimuthal distribution of the red and blue FFs, with the red FFs peaking at the same PA as the galaxy major axis, while the blue FFs peak at $PA \sim 110^\circ$ which is the direction of NGC 1023A (while the distribution of other blue FFs shows no clear peak in PA).

The 27 blue and 81 red FFs have mean colours of $g - z = 0.95 \pm 0.03$ and 1.52 ± 0.01 , respectively. In Fig. 4, we show the mean colour of the blue and red FFs compared to the single stellar population models of Maraston (2005) with a Kroupa (2001) Initial Mass Function. The red FFs have colours associated with a metal-rich stellar population as expected if they formed from disc material. From Keck spectra, the red FFs are known to be metal rich and old (Larsen & Brodie 2002), which is consistent with Fig. 4.

The blue FFs are consistent with being very young (≤ 5 Gyr). Half of the blue FFs appear to be associated with NGC 1023A, which is thought to have interacted with NGC 1023 a few 100 Myr ago and is responsible for the $\sim 10^9 M_\odot$ of surrounding $H I$ (Capaccioli, Lorenz & Afanasjev 1986). Spectroscopy of two blue NGC 1023A star clusters have ages up to 500 Myr (Larsen & Brodie 2002), consistent with them forming during the interaction process. As the $H I$ gas is widely distributed around the NGC 1023 system the blue

FFs not coincident with NGC 1023A may also be a few 100 Myr old – follow-up spectroscopy is required. Thus, blue FFs may be the lower mass counterparts to tidal dwarf galaxies, forming out of the tidal debris of a past galaxy interaction.

4 CONCLUSIONS

Using a recently available mosaic of eight *HST*/ACS pointings in the g and z bands, we investigate the star cluster system of NGC 1023 measuring magnitudes, colours and effective radii. We identify the normal GC system of NGC 1023 with its red and blue subpopulations, and two particularly luminous and therefore dense GCs. Two UCD objects with effective radii ~ 10 pc are also found. In this paper, we focus on the faint, extended (effective radii > 7 pc) clusters called FFs. Such objects were originally discovered in NGC 1023 by Larsen & Brodie (2000) using two *HST*/WFPC2 pointings. With our more complete spatial coverage, we confirm the association of some 81 red FFs with the disc of NGC 1023 consistent with them being long-lived open clusters (albeit somewhat larger and more luminous than typical Milky Way open clusters). We also identify a population of 27 blue FFs, half of which appear to be associated with the dwarf satellite galaxy NGC 1023A (which was largely absent from the original *HST*/WFPC2 coverage). The others appear to be spatially coincident with the $H I$ gas that surrounds the NGC 1023 system. The blue FFs are consistent with young (few 100 Myr) star clusters that formed during the interaction between the two galaxies.

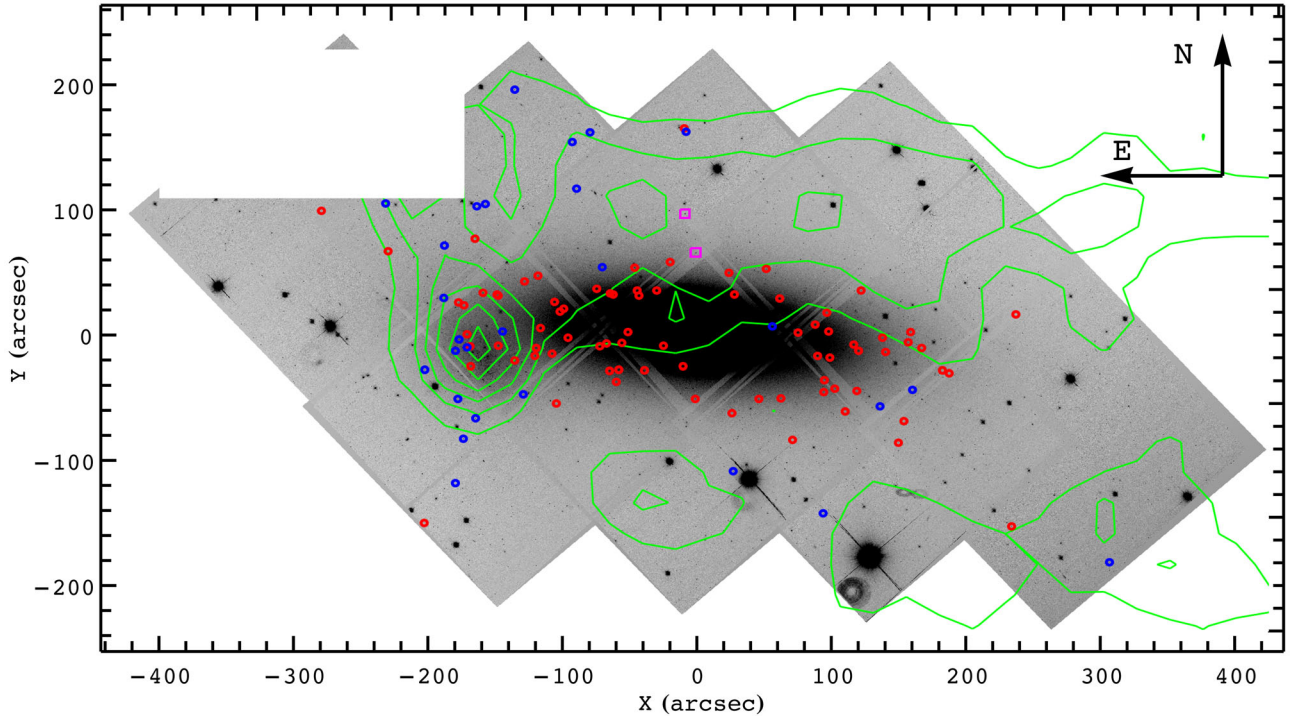


Figure 2. *HST*/ACS mosaic of NGC 1023. The location of red FF (red circles) and blue FF (blue circles) candidates are shown, along with two UCDs (magenta squares). The distribution of high-density H I (from Morganti et al. 2006) is shown by the green contours. The entire field of view of the mosaic covers about 12×7 arcmin². The H I contours peak on the dwarf satellite, NGC 1023A, which can be seen at ~ 140 arcsec east of NGC 1023 at PA $\sim 110^\circ$. Photometry of star clusters was carried out on individual pointings and not the mosaic shown here. The red FFs follow the general distribution of the galaxy disc, whereas roughly half of the blue FFs appear to be associated with NGC 1023A and the others with the densest H I gas.

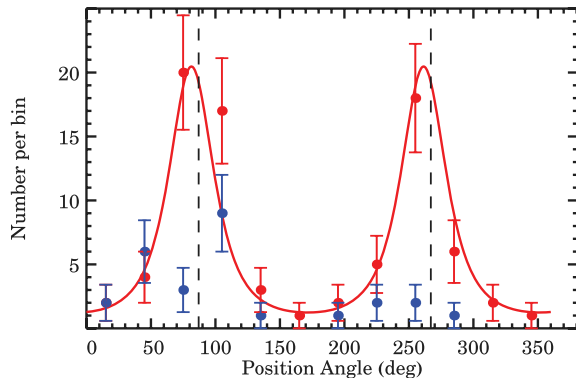


Figure 3. Azimuthal distribution of FF candidates in NGC 1023. The dashed lines represent the PAs of the major axis of NGC 1023, i.e. 85° and 265° . Red FFs (red circles for binned data and red line for a smooth model fit) show a peak at the same PAs as the galaxy major axis, while the blue FFs (blue circles) peak PA $\sim 110^\circ$ in the direction of NGC 1023A.

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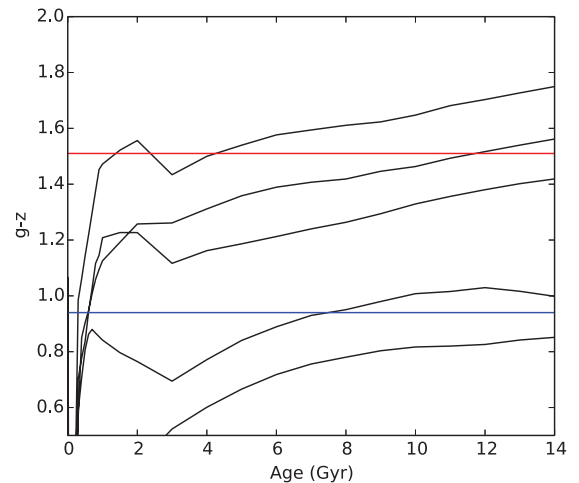


Figure 4. FF mean colours compared to stellar population models. The black solid lines show the evolution of $g - z$ colour with time for single stellar populations of different metallicities (i.e. $[Z/H] = -2.25, -1.35, -0.33, 0.00, +0.35$ from bottom to top) from the models of Maraston (2005). The solid red and blue lines show the mean $g - z$ colours of the red and blue FFs, respectively. The red FFs have colours associated with a metal-rich stellar population as expected if they formed from disc material, whereas the blue FFs are consistent with being very young (≤ 2 Gyr) as expected if formed moderately enriched gas during the recent interaction with NGC 1023A.

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Table 1. Star clusters in NGC 1023 (<http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stu940/-/DC1>).

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