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# A ‘super’ star cluster grown old: the most massive star cluster in the Local Group

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## ABSTRACT

We independently redetermine the reddening and age of the globular cluster (GC) 037–B327 in M31 by comparing independently obtained multicolour photometry with theoretical stellar population synthesis models. 037–B327 has long been known to have a very large reddening value, which we confirm to be  $E(B - V) = 1.360 \pm 0.013$ , in good agreement with the previous results. We redetermine its most likely age at  $12.4 \pm 3.2$  Gyr.

037–B327 is a prime example of an unusually bright early counterpart to the ubiquitous ‘super’ star clusters presently observed in most high-intensity star-forming regions in the local Universe. In order to have survived for a Hubble time, we conclude that its stellar initial mass function (IMF) cannot have been top-heavy. Using this constraint, and a variety of simple stellar population (SSP) models, we determine a photometric mass of  $\mathcal{M}_{GC} = (3.0 \pm 0.5) \times 10^7 M_{\odot}$ , somewhat depending on the SSP models used, the metallicity and age adopted and the IMF representation. This mass, and its relatively small uncertainties, makes this object the most massive star cluster of any age in the Local Group. Assuming that the photometric mass estimate thus derived is fairly close to its dynamical mass, we predict that this GC has a (one-dimensional) velocity dispersion of the order of  $(72 \pm 13)$  km s<sup>-1</sup>. As a surviving ‘super’ star cluster, this object is of prime importance for theories aimed at describing massive star cluster evolution.

**Key words:** globular clusters: individual: 037–B327 – galaxies: individual: M31 – galaxies: star clusters.

## 1 INTRODUCTION

Among the Local Group of galaxies, M31 contains the largest population of globular clusters (GCs) and is the nearest analogue of the Milky Way. From the observational evidence collected thus far (see, e.g. Rich et al. 2005), the M31 GCs reveal some striking similarities to their Galactic counterparts (Fusi Pecci et al. 1994; Djorgovski et al. 1997; Barmby, Holland & Huchra 2002). For example, both GC systems seem to have similar mass-to-light ratios ( $M/L_s$ ), velocity dispersion–luminosity relations (see also de Grijs, Wilkinson & Tadhunter 2005) and structural parameters.

Since the pioneering work of Tinsley (1968, 1972) and Searle, Sargent & Bagnuolo (1973), evolutionary population synthesis modelling has become a powerful tool to interpret integrated spectrophotometric observations of galaxies and their subcomponents, such as star clusters (Anders et al. 2004). Such models, as, for example, developed by Bruzual & Charlot (1993, 1996), Leitherer & Heckman (1995), and Fioc & Rocca-Volmerange (1997), were comprehen-

sively compiled by Leitherer et al. (1996) and Kennicutt (1998). The evolution of star clusters is usually modelled by means of the simple stellar population (SSP) approximation. An SSP is defined as a single generation of coeval stars formed from the same progenitor molecular cloud (thus implying a single metallicity), and governed by a given IMF. GCs, which are bright and easily identifiable, and whose populations in a given galaxy are typically characterized by homogeneous abundance and age distributions, are relatively easy to understand compared to the other mix of stellar populations in galaxies. Barmby & Huchra (2000) compared the predicted SSP colours of three stellar population synthesis models to the intrinsic broad-band *UBVIRJHK* colours of the Galactic and M31 GCs, and found that the best-fitting models match the clusters’ spectral energy distributions (SEDs) very well indeed. So, from the results of Barmby & Huchra (2000), there is evidence that the stellar population of GCs may be described by the SSPs of stellar population synthesis models. In fact, many authors have used SSP models to study the populations of clusters across the entire age range. For example, de Grijs et al. (2003b) simultaneously obtained ages, metallicities and extinction values for 300 clusters in NGC 3310, based on the archival *Hubble Space Telescope* (*HST*) observations from

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the ultraviolet to the near-infrared by means of a comparison between the observed SEDs and the predictions from the GALEV SSP models (Schulz et al. 2002; Anders & Fritze-v. Alvensleben 2003) (see also de Grijs et al. 2003c). Using their sophisticated and extensively validated method, de Grijs, Bastian & Lamers (2003a) obtained the age and mass estimates for 113 star clusters in the fossil starburst region B of M82 by comparing the observed cluster SEDs with the model predictions for an instantaneous burst of star formation. Bik et al. (2003) and Bastian et al. (2005) derived ages, initial masses and extinctions of M51 star cluster candidates by fitting the STARBURST99 SSP models (Leitherer et al. 1999) and GALEV for instantaneous star formation to the observed SEDs based on the *HST*/WFPC2 observations in six broad-band and two narrow-band filters. Ma et al. (2001, 2002a,b,c) and Jiang et al. (2003) estimated the ages of 180 star clusters in M33 and 172 GC candidates in M31 by comparing the SSP synthesis models of BC96 (Bruzual & Charlot 1996) with the integrated photometric measurements of these objects in the Beijing–Arizona–Taiwan–Connecticut (BATC) photometric system.

The study of M31 has been, and continues to be, a corner stone in extragalactic astrophysics (Barmby et al. 2000). The study of GCs in M31 can be traced back to Hubble (1932), who discovered 140 GCs with  $m_{\text{pg}} \leq 18$  mag. In this paper, we discuss the properties of the M31 GC B327 (where B indicates ‘Baade’) or Bo037 (Bo = ‘Bologna’, see Battistini 1987), which will subsequently be referred to as 037–B327, following the nomenclature introduced by Huchra, Brodie & Kent (1991). The extremely red colour of this object, combined with its apparent magnitude (given in their paper as  $V_0 = 16.97$  mag), was first noted by Kron & Mayall (1960), who suggested that this implied that the cluster must be highly reddened ( $A_V = 2.35$  mag) and extremely luminous,  $M_V^0 \simeq -11.5$  mag. Two years later, Vetešnik (1962a) determined magnitudes of 257 GC candidates in M31, including 037–B327, in the *UBV* photometric system. Using his photometric catalogue, Vetešnik (1962b) studied the intrinsic colours of the M31 GCs, and found that 037–B327 was the most highly reddened object in his sample of M31 GC candidates, with  $E(B - V) = 1.28$  mag. In order to avoid any a priori reason implying that the intrinsically brightest GCs in M31 should also be the most highly reddened, van den Bergh (1968, 1969) argued that  $R_V \equiv A_V/E(B - V) < 3.0$  in M31. Based on a re-analysis of the reddening towards the M31 GC population in general, and to 037–B327 in particular, Barmby, Perrett & Bridges (2002) argued that the evidence for an unusual reddening law is ‘somewhat less compelling’ than implied by van den Bergh (1968)’s arguments. Using low-resolution spectroscopy, Crampton et al. (1985) also found this cluster to be the most highly reddened GC candidate in M31, with  $E(B - V) = 1.48$  mag. Armed with a large database of multicolour photometry, Barmby et al. (2000) determined the reddening value for each individual M31 GC, including 037–B327, using the correlations between optical and infrared colours and metallicity based on various ‘reddening-free’ parameters, and found  $E(B - V) = 1.38 \pm 0.02$  mag for 037–B327 (P. Barmby, private communication). Using the spectroscopic metallicity to predict the intrinsic colours, Barmby et al. (2002) rederived the reddening value for this GC,  $E(B - V) = 1.30 \pm 0.04$  mag. Although the reddening values of 037–B327 based on a variety of methods are consistent, this value is unusually large and therefore worth verifying using independent methods. At the same time, the large reddening value makes 037–B327 the most *intrinsically* luminous GC in M31 (see details from Barmby et al. 2002).

In this paper, we first redetermine the reddening for 037–B327 by comparing observational SEDs (Section 2) with population synthe-

sis models in Section 3. Our independently determined results are in very good agreement with previous determinations. In Section 4, we then place this cluster in its evolutionary context, and conclude that 037–B327 is, in fact, not only a surviving ‘super’ star cluster, but also the most massive cluster of any age known in the Local Group. We summarize our results in Section 5.

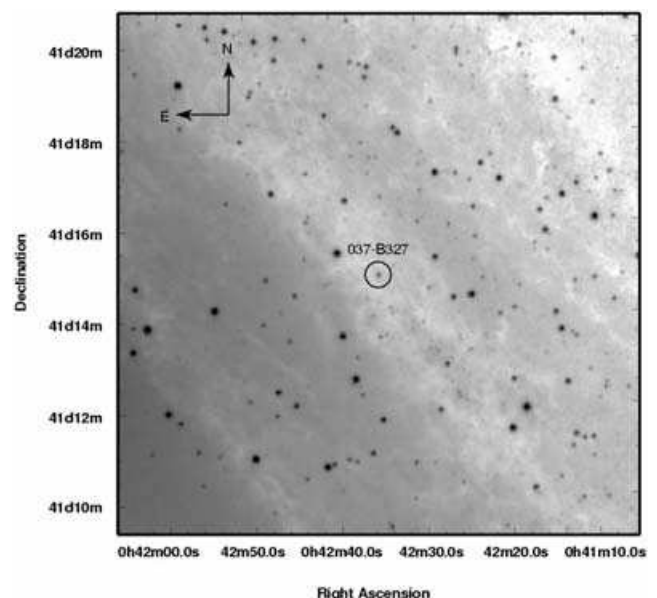
## 2 THE BATC, BROAD-BAND AND 2MASS PHOTOMETRY OF 037–B327

### 2.1 Archival images of the BATC sky survey

The observations of M31 were obtained by the BATC 60/90-cm *f*/3 Schmidt telescope located at the XingLong station of the National Astronomical Observatory of China (NAOC). This telescope is equipped with a Ford Aerospace 2048 × 2048K CCD camera with 15  $\mu\text{m}$  pixel size, giving a CCD field of view of 58 × 58 arcmin<sup>2</sup> with a pixel size of 1.7 arcsec. The BATC survey was carried out using 15 intermediate-band filters covering the optical wavelength range,  $\sim 3000$ – $10\,000$  Å. These filters were specifically designed to avoid contamination from the brightest and most variable night-sky emission lines. A description of the BATC photometric system can be found in Fan et al. (1996). The finding chart of 037–B327 in the BATC *g* band (centred on 5795 Å), obtained with the NAOC 60/90cm Schmidt telescope, is shown in Fig. 1.

### 2.2 Intermediate-band photometry of 037–B327

Jiang et al. (2003) extracted 123 images of M31 from the BATC survey archive, taken in 13 BATC filters (excluding the *a* and *b* filters) between 1995 September and 1999 December, and combined multiple images of the same filter to improve the image quality. Subsequently, they determined the magnitudes of 172 GCs, including 037–B327, in these 13 BATC filters based on the combined images using standard aperture photometry, that is, essentially by employing the PHOT routine in DAOPHOT (Stetson 1987). The BATC photometric system calibrates the magnitude zero level in a



**Figure 1.** An image of 037–B327 in the BATC *g* band obtained with the NAOC 60/90-cm Schmidt telescope. 037–B327 is circled. The field of view of the image is 11 × 11 arcmin<sup>2</sup>.

**Table 1.** The BATC photometry of the M31 GC 037–B327.

Filter	$\lambda_{\text{central}}$ (Å)	FWHM <sup>a</sup> (Å)	$N^b$	Magnitude
<i>c</i>	4210	320	3	19.28 (0.061)
<i>d</i>	4540	340	17	18.47 (0.032)
<i>e</i>	4925	390	11	17.81 (0.021)
<i>f</i>	5270	340	12	17.23 (0.016)
<i>g</i>	5795	310	7	16.40 (0.012)
<i>h</i>	6075	310	5	16.14 (0.009)
<i>i</i>	6656	480	3	15.54 (0.007)
<i>j</i>	7057	300	12	15.25 (0.006)
<i>k</i>	7546	330	6	14.89 (0.006)
<i>m</i>	8023	260	12	14.61 (0.004)
<i>n</i>	8480	180	5	14.32 (0.007)
<i>o</i>	9182	260	18	13.95 (0.004)
<i>p</i>	9739	270	12	13.78 (0.005)

<sup>a</sup>FWHM is full width at half-maximum. <sup>b</sup> $N$  is the number of images taken by the BATC survey.

similar fashion to the spectrophotometric AB magnitude system. For the flux calibration, the Oke–Gunn primary flux standard stars HD 19445, HD 84937, BD +26°2606, and BD +17°4708 (Oke & Gunn 1983), were observed during photometric nights (Yan et al. 2000). Table 1 lists the resulting BATC photometry of 037–B327.

### 2.3 The broad-band and 2MASS photometry of 037–B327

In order to estimate the reddening value of 037–B327 accurately, we try to use as many photometric data points covering as large a wavelength range as possible. Using the 4-Shooter CCD mosaic camera and the Smithsonian Astrophysical Observatory (SAO) infrared imager on the 1.2-m telescope at the Fred Lawrence Whipple Observatory (FLWO), Barmby et al. (2000) presented optical and infrared photometric data for 285 M31 GCs (see table 3 of Barmby et al. 2000). However, for 037–B327, only photometric measurements through the *BVRI* filters were listed. Sharov & Lyutyi (1981) presented the photoelectric *UBV* photometry of 110 M31 GCs, including 037–B327, with the 6-m telescope of the SAO. We adopted their photometric data point in the *U* band, with a photometric uncertainty of 0.08 mag, as suggested by Galleti et al. (2004).

Using the Two-Micron All-Sky Survey (2MASS) database, Galleti et al. (2004) identified 693 known and candidate GCs in M31, and presented their 2MASS *JHK*s magnitudes [Galleti et al. (2004) transformed all 2MASS magnitudes to the Palomar and Mount Wilson Observatories photometric system (Elias et al. 1982, 1983) using the colour transformations in Carpenter (2001)]. In this paper, we need the 2MASS *JHK*s magnitudes for 037–B327 in order to compare our observational SED to the SSP models, so we reversed this transformation using the same procedures. Since Galleti et al. (2004) did not give the 2MASS *JHK*s photometric uncertainties, we adopted 0.03 mag for all of the *J*, *H*, and *K*s bands. We obtained these uncertainty estimates by comparing the photometry of 037–B327 with fig. 2 of Carpenter, Hillenbrand & Skrutskie (2001) who plotted the observed photometric rms uncertainties in the time-series as a function of magnitude for stars brighter than their observational completeness limits. In fact, the photometric uncertainties adopted do not affect our results significantly. The broad-band and 2MASS photometric data points of 037–B327 are listed in Table 2.

**Table 2.** The broad-band and 2MASS photometry of the M31 GC 037–B327.

Filter	Magnitude	Reference
<i>U</i>	20.10 (0.08)	Sharov & Lyutyi (1981)
<i>B</i>	18.87 (0.05)	Barmby et al. (2000)
<i>V</i>	16.82 (0.05)	
<i>R</i>	15.54 (0.05)	
<i>I</i>	14.19 (0.05)	
<i>J</i>	12.24 (0.03)	Galleti et al. (2004)
<i>H</i>	11.26 (0.03)	
<i>K<sub>s</sub></i>	11.02 (0.03)	

## 3 PARAMETER DETERMINATIONS FOR 037–B327

### 3.1 Stellar populations and synthetic photometry

To estimate the reddening and age of 037–B327, we compare its SED with theoretical stellar population synthesis models. We used the SSP models of Bruzual & Charlot (2003, hereafter BC03), which have been upgraded from the Bruzual & Charlot (1993, 1996) version, and now provide the evolution of the spectra and photometric properties for a wider range of stellar metallicities. BC03 provided 26 SSP models (both of high and low resolution) using the 1994 Padova evolutionary tracks, 13 of which were computed using the Chabrier (2003) IMF assuming lower and upper mass cut-offs of  $m_L = 0.1 M_{\odot}$  and  $m_U = 100 M_{\odot}$ , respectively, while the other 13 were computed using the Salpeter (1955) IMF with the same mass cut-offs. In addition, BC03 provided 26 SSP models using the 2000 Padova evolutionary tracks. However, as BC03 pointed out, the 2000 Padova models, which include more recent input physics than the 1994 models, tend to produce worse agreement with observed galaxy colours. These SSP models contain 221 spectra describing the spectral evolution of an SSP from 0 to 20 Gyr. The evolving spectra include the contribution of the stellar component in the range from 91 Å to 160 μm. In this paper, we adopt the high-resolution SSP models computed using the 1994 Padova evolutionary tracks and Salpeter (1955) IMF.<sup>1</sup>

We convolve the SSP SEDs from BC03 with the BATC intermediate-band, broad-band *UBVRI* and 2MASS filter response functions to obtain synthetic optical and near-infrared photometry for comparison. The synthetic *i*th filter magnitude can be computed by

$$m = -2.5 \log \frac{\int_{\lambda} F_{\lambda} \varphi_i(\lambda) d\lambda}{\int_{\lambda} \varphi_i(\lambda) d\lambda} - 48.60, \quad (1)$$

where  $F_{\lambda}$  is the theoretical SED and  $\varphi_i$  the response function of the *i*th filter of the BATC, *UBVRI* and 2MASS photometric systems. Here,  $F_{\lambda}$  varies with age and metallicity.

<sup>1</sup> We note that because of the slow SED evolution of SSPs at ages in excess of a few Gyr, all of the most commonly used spectral synthesis models agree very well at these ages. Therefore, the choice of IMF is *only* important for estimating the photometric mass of the cluster (which we will discuss in Section 4), and does *not* affect the determination of the age and reddening parameters of 037–B327.

### 3.2 Metallicity of 037–B327

The SEDs of clusters are significantly affected by the metallicity one adopts. Using the Wide Field Fibre Optic Spectrograph at the William Herschel 4.2-m telescope, Perrett et al. (2002) obtained spectra of over 200 M31 GCs, including 037–B327. They determined a metallicity for 037–B327 of  $[Fe/H] = -1.07 \pm 0.20$  (or  $Z = 0.0017$ ), which we adopt here.

### 3.3 Fit results

We use a  $\chi^2$  minimization test to examine which BC03 SSP models are most compatible with the observed SED, following

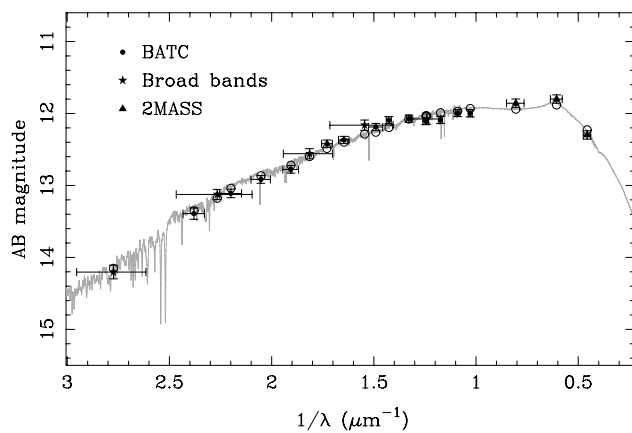
$$\chi^2 = \sum_{i=1}^{21} \frac{[m_{\lambda_i}^{\text{intr}}(E(B-V)) - m_{\lambda_i}^{\text{mod}}(t)]^2}{\sigma_i^2}, \quad (2)$$

where  $m_{\lambda_i}^{\text{mod}}(t)$  is the integrated magnitude in the  $i$ th filter of an SSP at age  $t$ ,  $m_{\lambda_i}^{\text{intr}}(E(B-V))$  presents the intrinsic integrated magnitude in the same filter, and

$$\sigma_i^2 = \sigma_{\text{obs},i}^2 + \sigma_{\text{mod},i}^2. \quad (3)$$

Here,  $\sigma_{\text{obs},i}^2$  is the observational uncertainty, and  $\sigma_{\text{mod},i}^2$  is the uncertainty associated with the model itself, for the  $i$ th filter. Charlot, Worthey & Bressan (1996) estimated the uncertainty associated with the term  $\sigma_{\text{mod},i}^2$  by comparing the colours obtained from different stellar evolutionary tracks and spectral libraries. Following Wu et al. (2005), we adopt  $\sigma_{\text{mod},i}^2 = 0.05$  in this paper.

The BC03 SSP models include six initial metallicities, 0.0001, 0.0004, 0.004, 0.008, 0.02 (solar metallicity), and 0.05. Spectra for other metallicities can be obtained by linear interpolation of the appropriate spectra for any of these metallicities. We treat  $E(B-V)$  as a fit parameter, to be determined simultaneously with the cluster age. The values for the extinction coefficient,  $R_i$ , are obtained by interpolating the interstellar extinction curve of Cardelli, Clayton & Mathis (1989). In Fig. 2, we show the intrinsic SED of 037–B327 and the SED of the best-fitting model. The best-reduced  $\chi^2_{\text{min}}$  is achieved with a reddening value of  $E(B-V) = 1.360 \pm 0.013$  mag and an age of  $12.4 \pm 3.2$  Gyr ( $1\sigma$  uncertainties). The former is in good agreement with previous results, that is,  $E(B-V) = 1.28$  obtained by Vetešnik (1962b),  $E(B-V) = 1.38 \pm 0.02$  of Barmby

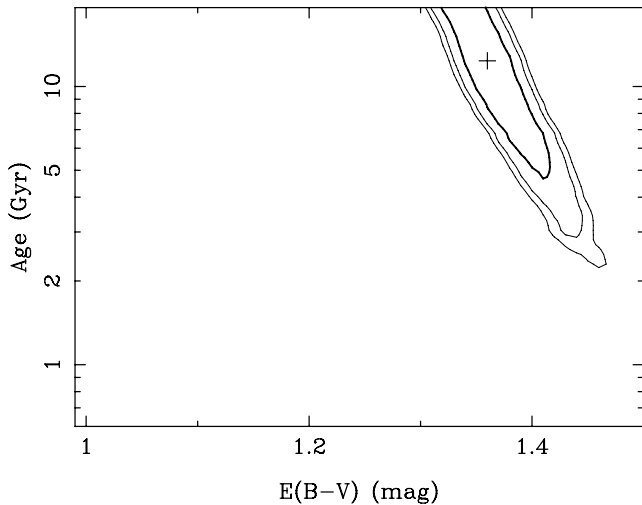


**Figure 2.** Comparison of the best-fitting integrated theoretical SED with the intrinsic SED of 037–B327. The photometric data points are shown as the symbols with error bars (vertical error bars for photometric uncertainties and horizontal ones for the approximate wavelength coverage of each filter). Open circles represent the calculated magnitude of the model SED for each filter.

et al. (2000), and  $E(B-V) = 1.30 \pm 0.04$  of Barmby et al. (2002). Fig. 3 shows the contours of the 99.7, 95.4 and 68.3 per cent confidence levels in the age–reddening plane for 037–B327. In order to support our claim that the best fit in Fig. 2 is reasonable, in Fig. 4, we show comparisons between the observed SED of 037–B327 and theoretical SEDs covering a range in ages and reddening values. It is clear that the theoretical SEDs with the  $E(B-V) = 1.00$  and 1.50 mag do not fit the observed SED of 037–B327 satisfactorily. Similarly, the theoretical SED of 5.0 Gyr does not fit the observed SED of 037–B327 satisfactorily either, once again supporting our result that this is an old GC, at least older than a few Gyr. On the other hand, theoretical SEDs with age of up to 17.0 Gyr would fit the observed SED of 037–B327 reasonably well. In fact, the theoretical SEDs are not sensitive to the variation of age for ages greater than  $\sim 10$  Gyr. Thus, here we show robustly that this cluster is as old as the majority of the Galactic GCs. Theoretical SEDs are sensitive to variations in reddening, in particular when one has access to a large wavelength coverage. Therefore, we conclude that the reddening value obtained in this paper is robust. Deep observations of high spatial resolution, taken with the Advanced Camera for Surveys on board the *HST* in the *F606W* filter show that 037–B327 is partially crossed by a dust lane, which might be responsible for the bulk of the reddening (Ma et al. 2006). The non-uniform optical depth across the object may artificially redden its colours, with as a consequence that the age obtained in this paper may be somewhat older than the cluster’s true age. However, since we cannot disentangle these effects from the ground-based photometric measurements owing to the high spatial resolution required for this (Ma et al. 2006), the impact of the partial dust lane coverage cannot be quantified at present. However, we point out that the dust lane crosses the object in its periphery, and does not significantly affect the bright core that dominates our integrated photometry. As such, we believe that the importance of this non-uniform reddening is limited. Nevertheless, we will take this effect into account in Section 4, where we will assume a lower age limit of 5 Gyr in order to validate the robustness of our main results.

At the same time, however, Ma et al. (2006) derived that 037–B327 has a high mean ellipticity,  $\epsilon \simeq 0.23$ , which could either imply that this cluster may not be very old, or that it has recently been affected by significant tidal forces such as those owing to a close encounter with a giant molecular cloud in the disc of the galaxy (cf. Gieles et al., in preparation). The ellipticity of a cluster by itself cannot be taken as evidence of a cluster being either young or old, however, although older clusters are in general believed to be more spherical than younger ones. For instance, in the Magellanic Clouds one finds non-spherical clusters of all ages (van den Bergh 1991; Goodwin 1997), while Stephens, Catelan & Contreras (2006) showed for the case study of WLM-1, the lone GC associated with the low-mass dwarf irregular galaxy WLM, that it is highly elliptical (yet non-rotationally flattened) despite its old age. We should keep in mind that although the age of 037–B327 obtained in this paper is model-dependent, independent studies based on the photometry alone suggest an age of  $\gtrsim 10$  Gyr (e.g. Jiang et al. 2003), the range of which is encompassed by our uncertainty estimate. Spectroscopic follow-up observations are required to determine the cluster’s age more conclusively. Colour–magnitude analysis of the high-resolution ACS images will not be able to improve this situation because of the very crowded cluster field at the distance of M31.

Jiang et al. (2003) estimated the age of 037–B327 at 9.75 Gyr, based on only the BATC data and on the SSP models of Bruzual & Charlot (1996; hereafter BC96); the reddening value adopted



**Figure 3.** Likelihood contour plot in the age–reddening plane for 037–B327, using the BC03 models. The favoured solution has a cluster age of 12.4 Gyr and a reddening of  $E(B - V) = 1.36$  mag. The contours shown are for the 99.7, 95.4 and 68.3 per cent confidence levels.

by Jiang et al. (2003) was  $E(B - V) = 1.38 \pm 0.02$  (Barmby et al. 2000). Jiang et al. (2003) only used the BC96 models for three metallicities, that is, 0.0004, 0.004 and 0.02, and did not linearly interpolate to find the best-fitting model. They adopted

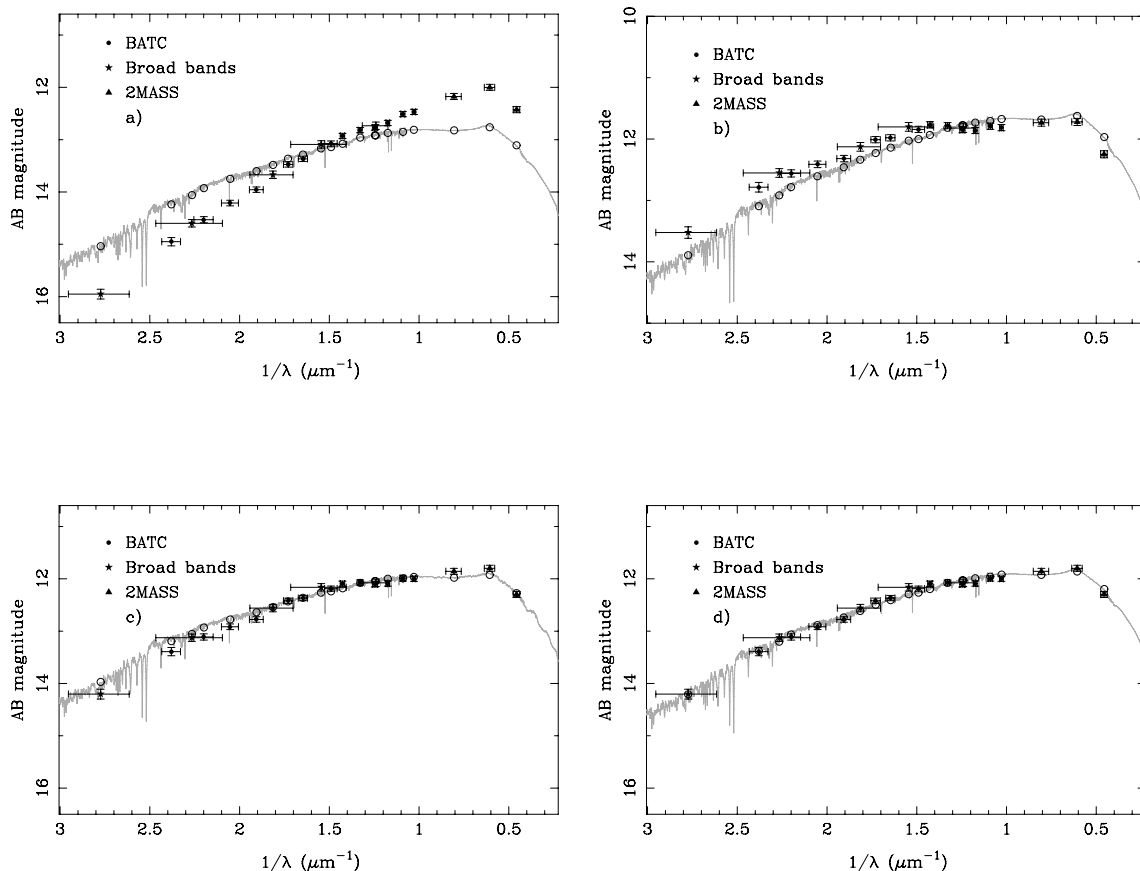
$Z = 0.004$ , significantly more metal-rich than the metallicity of 0.0017 adopted in this paper which was obtained by Perrett et al. (2002) from the spectra (see details from Section 3.2). For old GCs, the age–metallicity degeneracy becomes important. As a consequence, we conclude that the age of 037–B327 obtained by Jiang et al. (2003) is younger than its true age. From the results presented in this paper, we conclude that 037–B327 is as old as the majority of the Galactic GCs.

#### 4 A ‘SUPER’ STAR CLUSTER COME OF AGE?

With the basic parameters of 037–B327 now firmly established after our redetermination based on independent observational data, and on an independent modelling approach, we can now place the origin and early evolution of this extraordinary object in the context of the most violently star-forming events in the present-day local Universe.

In the past decade, it has become increasingly clear that the most violently star-forming episodes in the local Universe, such as those associated with major galaxy mergers and starburst events, produce a plethora of young massive star clusters (YMCs), often confusingly referred to as ‘super’ star clusters by virtue of their high luminosities (Whitmore et al. 1999; de Grijs et al. 2003a,b,c, and references therein).

The issue as to whether at least some of these YMCs might survive for up to a Hubble time, to eventually evolve into somewhat more metal-rich counterparts to the ubiquitous GC populations in the local Universe, has sparked a lively, and ongoing, debate. In



**Figure 4.** Comparison of the observed SED of 037–B327 with theoretical SEDs covering a range in ages and reddening values. The symbols are as in Fig. 2. (a) for an age of 12.4 Gyr, and  $E(B - V) = 1.00$  mag; (b) as (a), but for  $E(B - V) = 1.50$  mag; (c) for  $E(B - V) = 1.36$  mag, and an age of 5.0 Gyr; (d) as (c), but for an age of 17.0 Gyr.

**Table 3.** 037–B327 as a ‘super’ star cluster.

SSP models	IMF <sup>a</sup>	Metallicity (Z)	$M_V^0(t = 10 \text{ Myr})$ (mag)	$\mathcal{M}_{GC}$ ( $\times 10^7 M_\odot$ )
BC03 <sup>b</sup>	Chabrier (2003)	0.0001	$-16.65^{+0.25}_{-0.22}$	$2.8^{+0.5}_{-0.7}$
		0.0004	$-16.91 \pm 0.24$	$2.7^{+0.5}_{-0.8}$
	Salpeter (1955)	0.0001	$-16.38^{+0.23}_{-0.16}$	$3.5^{+0.5}_{-0.7}$
		0.0004	$-16.64 \pm 0.20$	$3.3^{+0.6}_{-0.7}$
GALEV	Salpeter (1955)	0.0004	$-17.14^{+0.24}_{-0.22}$	$2.7^{+0.5}_{-0.6}$
	Kroupa (2001)	0.0004	$-17.07^{+0.25}_{-0.22}$	$1.5 \pm 0.3$

<sup>a</sup>All IMFs were populated from 0.1 to 100  $M_\odot$ . <sup>b</sup>Using the 1994 Padova evolutionary tracks.

essence, the survival chances of YMCs for any significant length of time depend crucially on the stellar IMF as well as on environmental factors (cf. Smith & Gallagher 2001; de Grijs et al. 2005). If the stellar IMF is either too shallow (i.e., containing too many high-mass stars with respect to the low-mass fraction of the population), or characterized by a low-mass cut-off at stellar masses  $m_* \gtrsim 1 M_\odot$ , a cluster cannot survive for more than  $\sim 1$  Gyr (e.g. Gnedin & Ostriker 1997; Goodwin 1997; Smith & Gallagher 2001; Mengel et al. 2002).

The mere fact that this GC has reached an age of  $12.4 \pm 3.2$  Gyr places useful constraints on its stellar IMF, irrespective of the cluster’s current or initial mass. In particular, it implies that 037–B327’s stellar IMF must have had a significant fraction of low-mass stars, so that IMF descriptions including a low-mass cut-off above a few  $M_\odot$  are ruled out. We cannot, however, distinguish between the ‘standard’ Salpeter (1955) IMF and more modern IMF representations that include shallower slopes below  $\sim 1 M_\odot$ .

Based on its present luminosity,  $V = 16.82 \pm 0.05$  mag and very high extinction,  $E(B - V) = 1.36 \pm 0.01$ , its intrinsic luminosity,  $V_0 = 12.62 \pm 0.12$  mag [assuming the Cardelli et al. (1989) Galactic reddening law;  $A_V = 4.20 \pm 0.12$  mag] makes it the intrinsically most luminous GC in M31 (cf. Barmby et al. 2002).

We will now take this interpretation one step further, by employing a number of commonly used SSP models to evolve its luminosity back to a fiducial age of 10 Myr, so that we can compare its properties with those expected for YMCs and ‘super’ star clusters. In addition, we can now use the IMF constraint obtained above to bracket the most likely mass of 037–B327. We list the fiducial absolute  $V$ -band magnitudes at 10 Myr, corrected for foreground extinction, as well as our mass estimates based on a variety of relevant SSP models in Table 3.

Close inspection of the values for  $M_V^0(t = 10 \text{ Myr})$  shows that, when it was newly formed, this cluster truly belonged to the exceptional class of the ‘super’ star clusters. Few, if any, YMCs in the local Universe exhibit similarly high intrinsic luminosities. Notable exceptions are NGC 7252–W3 ( $M_V^0 \simeq -16.2$  mag, at a current age of  $\sim 0.3$  Gyr; Maraston et al. 2004), the brightest star cluster-like object in NGC 6745 ( $M_V^0 \simeq -13.3$  mag at a current age of  $\sim 1$  Gyr; de Grijs et al. 2003c), as well as M82–F and a few nuclear star clusters (see for an overview, table 1 in de Grijs et al. 2005).

Our mass estimates,  $\mathcal{M}_{GC} \gtrsim 2 \times 10^7 M_\odot$ , place it firmly at the top of the cluster mass function in the Local Group. Barmby et al. (2002)’s earlier mass estimate of  $\mathcal{M}_{GC} \sim 8.5 \times 10^6 M_\odot$  was based on a photometric mass estimate using a generic  $M/L$ ,  $M/L = 2$ , which was clearly somewhat low for its age. Here we have shown

that, irrespective of the SSP models and stellar IMF representation assumed, and taking the uncertainties in the object’s metallicity and age into account, the cluster is significantly more massive than both G1 in M31 ( $\mathcal{M}_{G1} = (7\text{--}17) \times 10^6 M_\odot$ ; Meylan et al. 2001) and  $\omega$  Cen in the Milky Way ( $\mathcal{M}_{\omega\text{Cen}} = (2.9\text{--}5.1) \times 10^6 M_\odot$ ; Meylan 2002), the next most massive clusters (of any age) in the Local Group.<sup>2</sup>

Because of the key constraints, we were able to place on the shape of the low-mass range of the stellar IMF, and the fact that our photometric mass estimates are all within each other’s uncertainty ranges [with the exception of the result based on the Kroupa (2001) IMF], we predict that dynamical mass estimates will yield very similar results. Unfortunately, there are no velocity dispersion measurements for 037–B327 available, however. Using the archival *HST/ACS* (Wide Field Camera) observations in the *F606W* and *F814W* filters (programme GO-10260; PI Harris), we obtained the half-light radii at the respective wavelengths of these filters. The half-light radii obtained, corrected (in quadrature) for the intrinsic size of the point spread function, are  $(0.52 \pm 0.04)$  and  $(0.53 \pm 0.04)$  arcsec for *F606W* and *F814W*, respectively, corresponding to the linear sizes of  $(2.52 \pm 0.19)$  and  $(2.57 \pm 0.19)$  pc, respectively, at the distance of M31,  $m - M = 24.88$  mag. If we combine these half-light radii with the photometric mass determinations for 037–B327, we predict (using the virial approximation) that its (one-dimensional) velocity dispersion will be of the order of  $(72 \pm 13) \text{ km s}^{-1}$ , if our IMF assumptions are valid (see, e.g. Maraston et al. 2004). Therefore, spectroscopic observations at a resolution of  $R \equiv \lambda/\Delta\lambda \gtrsim 4200$  (e.g.  $\Delta\lambda \gtrsim 2 \text{ \AA}$  at  $\lambda \sim 8500 \text{ \AA}$ , that is, in the calcium triplet region) will be able to confirm our conclusions regarding the low-mass IMF shape of this GC.<sup>3</sup>

We conclude, therefore, that 037–B327 is the current best example of a ‘super’ star cluster that has come of age, and as such an important object for theorists to take into account when developing models aimed at describing the evolution of the YMCs seen in large numbers in nearby starburst and galaxy merger environments.

<sup>2</sup> Even in the unlikely event that we have overestimated the cluster’s age significantly, and that its true age is  $\sim 5$  Gyr, this would reduce the derived photometric cluster mass by only a factor of  $\lesssim 2$ , depending on the metallicity and IMF assumed. Our claim that this cluster is the most massive star cluster in the Local Group, of any age, is therefore robust.

<sup>3</sup> We note that our virial approximation is based on a generic stellar population of equal-mass stars, and does not take into account the effects of mass segregation. However, these effects will affect the predicted velocity dispersion by an amount that is expected to be within our current uncertainty estimate.

## 5 SUMMARY AND CONCLUSIONS

In this paper, we first redetermined the reddening and age of the M31 GC 037–B327 by comparing its independently obtained multicolour photometry with theoretical stellar population synthesis models. Our multicolour photometric data are from *UBVRI*, 13 intermediate-band filters and *JHKs*, which constitute an SED covering  $\sim 3000\text{--}20\,000\text{ \AA}$ . The reddening towards this cluster, which we determine at  $E(B - V) = 1.360 \pm 0.013$  mag, was also estimated by Barmby et al. (2000) and Barmby et al. (2002), using the correlations between optical and infrared colours and metallicity, by defining various ‘reddening-free’ parameters, and by using the spectroscopic metallicity to predict the intrinsic colours. These three different methods yield very consistent reddening values. The age of  $12.4 \pm 3.2$  Gyr for 037–B327 obtained in this paper shows that 037–B327 is a GC as old as the majority of the Galactic GCs.

Subsequently, we placed the origin and early evolution of this M31 GC in the context of the YMCs currently being observed in major starbursts and galaxy mergers in the local Universe. 037–B327 is a prime example of an unusually bright early counterpart to the ubiquitous ‘super’ star clusters presently observed in most high-intensity star-forming regions. In order to have survived for a Hubble time, we conclude that its stellar IMF cannot have been top-heavy, that is, characterized by a low-mass cut-off at  $m_* \gtrsim 1 M_\odot$ , as sometimes advocated for current ‘super’ star clusters. Using this constraint, and a variety of SSP models, we determine a photometric mass for 037–B327 of  $M_{GC} = (3.0 \pm 0.5) \times 10^7 M_\odot$ , somewhat depending on the SSP models used, the metallicity and age adopted and the IMF representation. In view of the large number of free parameters, the uncertainty in our photometric mass estimate is surprisingly small. This mass, and its relatively small uncertainties, make this object the most massive star cluster of any age in the Local Group. Assuming that the photometric mass estimate thus derived is fairly close to its dynamical mass (based on the assumption of virial equilibrium), we predict that this GC has a (one-dimensional) velocity dispersion of the order of  $(72 \pm 13) \text{ km s}^{-1}$ , which – if confirmed using spectroscopic observations at  $R \gtrsim 4200$  – will serve as robust confirmation of our conclusions regarding the shape of the IMF. As a surviving ‘super’ star cluster, this object is of prime importance for theories aimed at describing massive star cluster evolution.

It has been speculated that some of the most-luminous known GCs in the Local Group, including  $\omega$  Centauri, G1-Mayall II and also NGC 2419 (but see de Grijs et al. 2005, for counter-arguments for this object), might be the remnant nuclei of tidally stripped dwarf galaxies (Zinnecker et al. 1988; Freeman 1993; Bassino, Muzzio & Rabolli 1994; van den Bergh & Mackey 2004). Ma et al. (2006) determined the structural parameters of 037–B327 by fitting the observed surface brightness distribution to a King profile, and found that this object falls in the same region of the  $M_V$  versus  $\log R_h$  diagram as do  $\omega$  Centauri, M54 and NGC 2419 in the Milky Way and the massive cluster G1 in M31. All four of these objects are claimed to be the stripped cores of former dwarf galaxies (see details from van den Bergh & Mackey 2004; Mackey & van den Bergh 2005). This suggests that 037–B327 may also be the stripped core of a former dwarf companion to M31. However, from ground-based observations of the brightest objects in NGC 5128, which is the nearest giant elliptical galaxy, Gómez et al. (2006) have concluded that clusters form a continuum in the  $M_V$  versus  $\log R_h$  diagram. So, it is difficult to distinguish between a GC and a stripped core of a dwarf. Future work is needed to confirm that 037–B327 is a GC or whether it might be a stripped core of a dwarf.

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