Imaging of the merging galaxy NGC 3597 and its population of protoglobular clusters

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ABSTRACT

We present wide field-of-view near-infrared imaging from the NTT and very deep optical imaging from the HST of the young merging galaxy NGC 3597. The morphology of the galaxy and the properties of the newly formed protoglobular clusters (PGCs) are examined. Our K-band data reveal the presence of a second nucleus, which provides further evidence that NGC 3597 is the result of a recent merger. Combining new K-band photometry with optical photometry, we are able for the first time to derive a unique age for the newly formed PGCs of a few Myr. This is consistent with the galaxy starburst age of \#10 Myr. From deep HST imaging, we are able to probe the luminosity function, 8 magnitudes fainter than normal, old globular clusters, and confirm that the PGCs have a power-law distribution with a slope of \#\sim2.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: individual: NGC 3597 – galaxies: interactions – galaxies: photometry – galaxies: star clusters.

1 INTRODUCTION

In the 1970s, the rich globular cluster (GC) populations seen around elliptical galaxies were used to argue against the idea that ellipticals formed from the simple merger of two spirals (van den Bergh 1975). The suggested solution to this problem was the creation of new GCs from the gas associated with the progenitor galaxies (Schweizer 1987; Ashman & Zepf 1992). The Hubble Space Telescope (HST), with its high spatial resolution, has indeed detected protoglobular cluster candidates in several merging galaxies. Over a dozen such systems have now been observed with the HST (e.g. Holtzman et al. 1992, 1996; Whitmore et al. 1993; Whitmore & Schweizer 1995; Schweizer et al. 1996; Miller et al. 1997; Carlson et al. 1998; Zepf et al. 1999). These studies suggest that all mergers involving gaseous systems create protoglobular clusters (PGCs). However, there are several outstanding issues concerning these PGCs, such as the total number created, their luminosity (mass) function, their destruction rate, and the overall specific frequency of the final system (e.g. Brodie et al. 1998; Kissler-Patig, Forbes & Minniti 1998; Forbes 1998; Zepf et al. 1999).

Perhaps the first detailed study of PGCs in a merging system was that of Lutz (1991). Lutz presented optical imaging and spectroscopy of NGC 3597 (AM 1112 – 232). Classified as an S0pec, it reveals an extended structure with plumes, but the main body of the galaxy resembles an \#14-like surface brightness profile. Using the ESO 2.2-m telescope, under \#1.3-arcsec seeing conditions, Lutz detected and measured photometry for 31 unresolved objects around the galaxy. About half of these were suggested to be young, blue PGCs. Following this groundbreaking work by Lutz, Holtzman et al. (1996) reobserved NGC 3597 using the WFPC2 camera on the HST. They detected over 70 PGC candidates. The bulk of these had similar colours, suggesting a single age and metallicity population. However, from their \#V – \#R colours alone they were unable to identify a unique age for the PGCs.

Here we present K-band (2.2-\mu m) imaging of NGC 3597, taken under photometric conditions with \#0.6-arcsec seeing. The near-infrared has the advantage of being much less affected by dust extinction (\#K ~ 0.1A\#V). We also incorporate deep B- and R-band data from the HST archive. The near-infrared photometry, when combined with optical magnitudes, provides a powerful constraint on the age of PGCs. After completing our study, Carlson et al. (1998) published a study of NGC 3597 using the same deep HST imaging. However, as described below, the deep B and R data alone do not provide a significant improvement over the Holtzman et al. V- and R-band data in determining the age of the PGCs. Our main contribution is the addition of new K-band photometry, which allows the age of the PGCs to be uniquely constrained for the first time. The K-band images also reveal a second nucleus, not obvious in the shorter wavelength HST images, but apparent from radio imaging.
2 NEAR-INFRARED DATA

2.1 Observations and data reduction

K short (Ks: λ/Δλ = 2.162/0.275) images of NGC 3597 were taken with the infrared camera SOFI on the ESO NTT over two nights in 1999 March. The data were obtained under photometric conditions and excellent seeing (0.6 arcsec). SOFI has a field-of-view of ~5 x 5 arcmin² and a pixel size of 0.292 arcsec. A total of 220 x 30-s exposures were taken to give a total effective exposure time of 110 min. Between each 30-s exposure, the telescope position was offset by ~1 arcmin. Standard stars from the list of Persson et al. (1998) were also taken before and after each block of galaxy observations.

Flat-fields were made by median-combining the standard star images. These were determined to be superior to the dome and twilight flats. After subtracting dark currents and flat-fielding, the individual images were carefully shifted and median-combined to form a single final Ks image of NGC 3597. The sky background of the final image is flat to ~2 per cent.

From our standard star images taken directly before and after the galaxy, we have determined a Ks zero-point of 22.23 ± 0.03, where the uncertainty represents the error on the mean from several different images. We will not attempt to transform our Ks magnitudes to standard K-band values, but simply note that they are similar and have been defined so that Ks = K for A0 standard stars (Persson et al. 1998). Hereafter we simply use K to refer to our K short-band data.

2.2 Galaxy modelling

We have modelled the galaxy using the STSDAS task ELLIPSE. The central position and the position angle of the model were fixed, but the ellipticity was allowed to vary. Stars and bright PGCs were masked out. We also used sigma clipping to exclude the most deviant data values from the model fit. Subtraction of the resulting galaxy model showed that it was a reasonable representation except in the very inner regions. The K surface brightness profile for the model is shown in Fig. 1. The outer regions are close to an r¹/₄ surface brightness profile, as found in most elliptical galaxies.

The total magnitude of the galaxy, from a curve-of-growth analysis, is K = 11.75 ± 0.05. We later use the model-subtracted image for the detection of GCs.

3 RESULTS AND DISCUSSION

3.1 The host galaxy

The basic properties of NGC 3597 are summarized in Table 1. Coordinates of the galaxy centre are taken from an HST R-band (F702W) image, but are probably only accurate to within ±1 arcsec due to dust. However, this position is consistent with the position of the brightest radio source (van Driel, van den Broek & de Jong 1991). The distance of 49 Mpc is based on a Virgo-centric inflow-corrected velocity of 3513 km s⁻¹ and H₀ = 75 km s⁻¹ Mpc⁻¹. At this distance, 1 arcsec corresponds to 240 pc. The galaxy is fairly luminous at all wavelengths, and is undergoing a vigorous starburst (e.g. Lutz 1991; Kim et al. 1995; Rephaeli, Gruber & Persic 1995).

In Fig. 2 we show the inner regions of our K image of NGC 3597. We also identify the location of the two radio sources mapped at 6 cm by van Driel et al. (1991), which correspond spatially with the bright central source and a second source in our K image. The galaxy inner regions reveal that the bright central source is connected via a ‘bridge’ to the second source about 3.8 arcsec (0.9 kpc) to the west. This could be simply a super starcluster, but it is not particularly bright at optical wavelengths. At radio wavelengths, it appears as a connected second source with a similar flux (S₂₁ cm = 18.0 mJy compared to the central source of 29.1 mJy). Thus it appears quite likely that the central source and the second source, seen in the K band and at 6 cm, are the nuclei of the merging galaxies. The dynamical time-scale for these nuclei to merge is less than 10⁶ yr, so we appear to be witnessing NGC 3597 in the very final stages of nuclear coalescence.

With a projected nuclear separation of 0.9 kpc, NGC 3597 is at a similar evolutionary stage to NGC 3256 (Norris & Forbes 1995) and NGC 6240 (van der Werf et al. 1993), with separations of 0.73 and 0.90 kpc respectively. The ratio of far-infrared (FIR) to H₂ mass is a measure of star formation efficiency, and has been shown to increase as the nuclear separation of two merging galaxies reduces to zero (Gao & Solomon 1999; Georgakakis, Wiklind et al. 1995; 3 = Lutz (1991); 4 = Rephaeli et al. (1995); 5 = Smith et al. (1993)).

Table 1. NGC 3597 properties.

| Property | Value | Ref. |
|----------|-------|------|
| α (J2000) | 11ʰ 14ᵐ 42ˢ | 1 |
| δ (J2000) | -23ʰ 43ᵐ 40ˢ | 1 |
| Type | S0pec | RC3 |
| B − V | 0.67 | 2 |
| Distance | 49.0 Mpc | 2 |
| M_B | −20.12 | 1 |
| M_K | −21.71 | 1 |
| L_α | 1.72 x 10¹⁰ L☉ | 1 |
| L_L | 9.82 x 10¹⁰ L☉ | 1 |
| L_FIR | 7.23 x 10¹⁰ L☉ | 2 |
| L_X | 1.2 x 10³⁷ erg s⁻¹ | 4 |
| L_21 cm | 2.7 x 10²⁶ erg s⁻¹ | 5 |
| M_α | 2.82 x 10¹⁰ M☉ | 2 |
| M_L | <2.6 x 10¹⁰ M☉ | 2 |
| M_α | 4.85 x 10⁹ M☉ | 2 |

References: 1 = this paper; 2 = Wiklind et al. (1995); 3 = Lutz (1991); 4 = Rephaeli et al. (1995); 5 = Smith et al. (1993).
Forbes & Norris, in preparation). NGC 3597 has a $L_{320}/M_*= 25.6$ (Wiklind, Combes & Henkel 1995), comparable to 20 for NGC 3256 and 30 for NGC 6240. This further supports the case that NGC 3597 is near the nuclear coalescence stage of a merger sequence.

Beyond our faintest isophote, deep optical images reveal plumes ($\mu_R \sim 25$ mag arcsec$^{-2}$) to the NW and SW (Lutz 1991). As NGC 3597 is relatively isolated, the outer morphological disturbance is almost certainly due to a merger of some sort. Indeed, the morphology of the plumes resembles the merger simulation shown in Barnes (1998) at 300 Myr after pericentre, and just before nuclear merger.

The galaxy is currently undergoing a starburst. Optical spectra (e.g. Lutz 1991; Kim et al. 1995) reveal emission lines indicative of H II regions. However, as well as the current star formation activity, there is also evidence that the burst is not instantaneous but has proceeded for some time. Optical spectra clearly show weak hydrogen absorption lines (along with the hydrogen emission) indicative of an earlier phase of star formation. The radio spectral index is $\alpha = -0.84$, indicating that the emission is not dominated by H II regions, but rather is due to non-thermal synchrotron emission from SNRs (Smith & Kassim 1993). Both the current and post-starburst contribute to the far-infrared luminosity of $L_{\text{FIR}} \sim 7 \times 10^9 L_\odot$, which is consistent with the well-known far-infrared versus radio correlation. Kim et al. estimated an H$\beta$ absorption EW of 2.5 Å from their optical spectrum. Such an EW occurs in the first 10 Myr of a starburst (e.g. Bruzual & Charlot 1993). This indicates that the starburst is very recent, starting less than 10 Myr ago and continuing to the present day. We compare this age estimate to that of the PGCs in the next section.

Wiklind et al. (1995) did not detect H I gas in NGC 3597, but only placed a relatively high upper limit of $M_{HI} < 2.6 \times 10^8 M_\odot$. Based on the FIR luminosity and a Galactic gas-to-dust ratio, Lutz (1991) estimated an H I mass of $3 \times 10^8 M_\odot$, i.e., almost a factor of 100 below the current Wiklind et al. limit. It would be interesting to place tighter limits on the H I mass and investigate the possibility that atomic hydrogen gas is being compressed during the merger into molecular gas.

Mihos & Hernquist (1994) have modelled the star formation history of equal-mass spiral galaxies. They found that for systems without strong bulges (e.g., Sc spirals), most of the merger-induced star formation occurs at the pericentre encounter over a times-scale of a few Myr. However, the presence of a bulge inhibits gas flow and delays the main starburst until nuclear coalescence. This starburst also lasts only a few Myr. The age of the starburst in NGC 3597 (i.e., $\leq$10 Myr) and the galaxy morphology (i.e., two nuclei and a common $r^{1/4}$-like envelope) suggests that the latter situation is correct. Thus it appears that NGC 3597 is the product of two near-equal-mass spirals, at least one of which contained a strong bulge. Furthermore, we are currently witnessing it at the nuclear merger stage, which is also the period of its most intense star formation activity.

3.2 The protoglobular clusters

Our $K$ image of NGC 3597 reveals a number of bright unresolved sources. The vast bulk of these are PGCs. They were first noticed by Lutz (1991) and later reobserved with HST (Holtzman et al. 1996; Carlson et al. 1998). In the discussion that follows we will assume a Galactic extinction towards NGC 3597 of $A_V = 0.12$ ($A_B = 0.16$, $A_R = 0.08$, and $A_K = 0.01$) as used by Holtzman et al. Although the galaxy shows a dust lane to the north of the nucleus, the internal extinction towards most of the PGCs is probably not large, given the relatively uniform $V-R$ colours noted by Holtzman et al. (see their fig. 6).

Lutz (1991) tabulated 31 sources. From Holtzman et al. (1996), it appears that nine of them are bona fide PGCs, i.e., numbers 10, 11, 13, 14, 17, 19, 21, 23 and 24 from his table (the other 22 sources are either foreground stars or background galaxies). The mean $B-V$ colour for these nine sources, corrected for Galactic extinction, is 0.40, with a 1σ error on the mean of 0.03. This colour and range for the PGCs are shown in Fig. 3, along with the evolutionary track for a solar-metallicity, Salpeter IMF single stellar population from Bruzual & Charlot (1993). The IMF and metallicity of the PGCs are of course unknown, so any derived ages will be a guideline only. The average PGC colour intersects
the track at about 6–10, 100 and 1000 Myr. Thus it is impossible to derive a unique age from the $B – V$ colour alone.

Holtzman et al. (1996) used WFPC2 to obtain F555W ($V$) and F702W ($R$) photometry of the PGCs. They detected 72 PGCs in the PC chip down to $V \approx 25.5$. The first source listed by Holtzman et al. (Holtz ID = 1) is probably a star with $V = 20.04$ and $V – K = 1.4$, which suggests that it is a G0 dwarf star. For the 60 globular clusters with $V < 25$, the mean colour and error on the mean is $V – R = 0.34 \pm 0.03$ (again corrected for Galactic extinction). This is shown in Fig. 4, along with the Bruzual & Charlot (1993) evolutionary track. As with $B – V$, the $V – R$ colours do not give a single age but several possibilities, i.e., $6$, $12$, $80$ and $200$ Myr. The $V – R$ colours do, however, rule out the oldest $B – V$ age of 1 Gyr.

Using the HST PGC positions, we measured $K$ magnitudes using daophot. This was carried out on the galaxy-subtracted image, using small-aperture magnitudes for which we then applied an aperture correction (based on objects away from the galaxy centre). We detected 31 PGCs in our image down to $K \approx 22.8$, although with large errors at faint magnitudes. Our $K$ magnitudes and measurement errors are listed in Table 2, along with the Holtzman et al. identification (ID) number and offset from the galaxy centre. All of these PGCs lie within $\approx 20$ arcsec of the galaxy centre (i.e., detected in the PC chip by Holtzman et al.).

In Table 3 we list the $V$ magnitude, $V – R$ colours and errors from Holtzman et al. (1996). The errors are photometric measurement errors, and do not include zero-point errors (on the order of 0.05–0.1 mag). These errors have been combined in quadrature to obtain the final $V – K$ error. The mean colour and error on the mean is $V – K = 0.95 \pm 0.14$. This range of colours is shown in Fig. 5, along with the Bruzual & Charlot (1993) evolutionary track. The extra ‘leverage’ from the $K$ band means that the $V – K$ colours of the PGCs intersect the track at only one place, i.e., around 5 Myr. This is consistent with the youngest age suggested by the $B – V$ and $V – R$ colours, and rules out the older ages at the $3\sigma$ level. Any correction for internal extinction, or if the PGCs had supersolar metallicities, would make the age even less than 5 Myr. Such an age should be regarded as somewhat qualitative, since it is dependent on unknown factors (e.g., the IMF) and on the particular stellar population model used (i.e., Bruzual & Charlot 1993).

We have obtained deep F450W ($B$) and F702W ($R$) HST images of NGC 3597 from the CADC HST archive. The eight images total 5200 s in $B$ and 5000 s in $R$, and cover essentially the same area as the shallower Holtzman et al. (1996) data. They were average-combined using the stsdas task gcombine, which effectively removes cosmic rays. The high throughput of the F702W filter and the spectral energy distribution of globular clusters mean that the $R$ image will be somewhat deeper than the $B$ image. Nevertheless, both images should reach magnitudes typical of the brighter GCs associated with the original, old population from the progenitor galaxies. The previous HST imaging published by Holtzman et al. (1996) had a F702W exposure time of 1100 s, and was thus not deep enough to reach the old population and probes only the bright end of the new population. These data were also recently used by Carlson et al. (1998), and reach about 1.6 mag deeper in $R$ than the Holtzman et al. study.

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**Figure 4.** $V – R$ colour evolution for a single stellar population of solar metallicity from Bruzual & Charlot (1993). The horizontal line and dashed lines show the mean $V – R$ colour and $1\sigma$ range for 71 protoglobal clusters (PGCs) from Holtzman et al. (1996). The PGCs could have several possible ages from $–6$ Myr to 200 Myr.

| Holtz ID | $\Delta\alpha$ ($^\circ$) | $\Delta\delta$ ($^\circ$) | $Ks$ (mag) | $\sigma(Ks)$ (mag) |
|---------|--------------------------|--------------------------|-----------|-------------------|
| 2       | –8.9                    | –9.8                     | 19.86     | 0.15              |
| 3       | –11.2                   | 7.6                      | 20.21     | 0.22              |
| 4       | –3.6                    | –17.0                    | 20.33     | 0.21              |
| 5       | 11.2                    | –0.7                     | 20.43     | 0.16              |
| 6       | –10.3                   | 0.3                      | 20.92     | 0.47              |
| 7       | 8.3                     | 4.7                      | 19.94     | 0.13              |
| 8       | 3.2                     | –5.9                     | 20.84     | 0.18              |
| 9       | –4.7                    | 15.0                     | 20.11     | 0.15              |
| 10      | 6.2                     | –6.8                     | 21.12     | 0.36              |
| 11      | –7.0                    | 1.6                      | 21.05     | 0.16              |
| 12      | –7.4                    | –2.2                     | 21.98     | 0.33              |
| 13      | –3.7                    | 4.4                      | 20.97     | 0.26              |
| 14      | 16.9                    | 11.5                     | 21.55     | 0.28              |
| 15      | 6.0                     | –15.0                    | 21.61     | 0.44              |
| 16      | –5.7                    | –1.7                     | ...       | ...               |
| 17      | –12.1                   | –8.3                     | 21.78     | 0.35              |
| 18      | –12.6                   | 2.0                      | 21.95     | 0.53              |
| 19      | –3.2                    | 6.9                      | 21.28     | 0.26              |
| 20      | –5.0                    | –5.2                     | 19.51     | 0.13              |
| 21      | 8.1                     | 3.8                      | 20.02     | 0.17              |
| 22      | 7.3                     | –6.1                     | ...       | ...               |
| 23      | –6.1                    | –0.6                     | ...       | ...               |
| 24      | –2.9                    | 12.2                     | ...       | ...               |
| 25      | –5.3                    | –7.1                     | 21.70     | 0.20              |
| 26      | 1.5                     | –12.1                    | 22.38     | 0.80              |
| 27      | –3.3                    | 6.6                      | 21.39     | 0.25              |
| 28      | –10                    | –0.5                     | 22.72     | 0.53              |
| 29      | 6.1                     | 7.7                      | 20.84     | 0.31              |
| 30      | 0.3                     | 15.2                     | ...       | ...               |
| 31      | 11.9                    | –3.4                     | 22.11     | 0.57              |
| 32      | –0.2                    | –14.7                    | ...       | ...               |
| 33      | 4.8                     | 5.5                      | 22.40     | 0.31              |
| 34      | 4.5                     | –7.4                     | 22.31     | 0.36              |
| 35      | –0.4                    | 4.7                      | 21.82     | 0.28              |
| 36      | –11.4                   | 5.0                      | 22.76     | 0.80              |
| 37      | 16.5                    | 9.9                      | ...       | ...               |
| 38      | 5.5                     | 8.1                      | 22.13     | 0.28              |
| 39      | 12.3                    | 5.5                      | 22.24     | 0.62              |
| 40      | –4.6                    | –10.7                    | ...       | ...               |

Notes: Protoglobal clusters within $\approx 20$ arcsec of the galaxy centre. The ID number and offset from the galaxy centre are from Holtzman et al. (1996). $Ks$ magnitudes and measurement errors are from this paper.
In order to locate sources, we used DAOFIND with a conservative 4σ per pixel detection criterion. For the PC chip, we fit the galaxy isophotes using ELLIPSE and subtracted off a model before running DAOFIND. Because of the confused nature of the central regions in the B image, due to dust and young star formation, we have excluded the central 9-arcsec radius from the automatic detection. Photometry on all four chips was measured using PHOT with a two-pixel-radius aperture. Aperture corrections to 0.5 arcsec and zero-points were taken from Holtzman et al. (1995, 1996). The objects on the PC chip are marginally resolved. Holtzman et al. (1996) showed that the bulk of objects required a typical correction of 0.22 mag, in addition to the above aperture correction, to include all of the light. Variations with the size of the object and its position on the chip could introduce another source of error on the order of 0.1 mag. However, the correction to total light affects the two filters almost equally, so there is little error introduced in the final B − R colour.

The resulting object lists were then checked visually on the image display to exclude the very few remaining obvious bright stars and background galaxies. At this stage, our candidate GC list contained 292 sources from all four chips (excluding the central 9 arcsec of the PC chip). A colour−magnitude diagram is shown in Fig. 6. We have adopted selection cuts of $0.5 < B − R < 2.0$ and $B < 27$. The colour cuts correspond to the full range expected.

### Table 3. Globular cluster colours.

| Holtz ID | Lutz ID | V   | σ(V) | V − R | σ(V − R) | V − K | σ(V − K) |
|---------|--------|-----|------|-------|----------|-------|----------|
| 2       | 13     | 20.31 | 0.01 | 0.30  | 0.01     | 0.45  | 0.15     |
| 3       | 21     | 20.39 | 0.01 | 0.21  | 0.01     | 0.18  | 0.22     |
| 4       | 10     | 20.58 | 0.01 | 0.21  | 0.01     | 0.25  | 0.21     |
| 5       | 17     | 21.08 | 0.01 | 0.31  | 0.01     | 0.65  | 0.16     |
| 6       | ...    | 20.84 | 0.01 | 0.21  | 0.01     | −0.08 | 0.48     |
| 7       | 19     | 21.39 | 0.02 | 0.49  | 0.04     | 1.45  | 0.13     |
| 8       | ...    | 21.24 | 0.01 | 0.27  | 0.01     | 0.41  | 0.18     |
| 9       | 24     | 21.02 | 0.01 | 0.21  | 0.02     | 0.91  | 0.15     |
| 10      | 21     | 21.62 | 0.01 | 0.26  | 0.01     | 0.50  | 0.36     |
| 11      | ...    | 21.92 | 0.02 | 0.31  | 0.04     | 0.88  | 0.16     |
| 12      | ...    | 21.88 | 0.02 | 0.29  | 0.04     | −0.10 | 0.32     |
| 13      | ...    | 21.66 | 0.03 | 0.29  | 0.05     | 0.69  | 0.26     |
| 14      | 23     | 22.32 | 0.02 | 0.30  | 0.02     | 0.77  | 0.28     |
| 15      | 11     | 22.16 | 0.02 | 0.26  | 0.01     | 0.56  | 0.44     |
| 16      | ...    | 22.32 | 0.04 | 0.57  | 0.07     | ...   | ...      |
| 17      | 14     | 21.91 | 0.02 | 0.18  | 0.03     | 0.14  | 0.35     |
| 18      | ...    | 22.14 | 0.02 | 0.26  | 0.03     | 0.19  | 3.61     |
| 19      | ...    | 22.33 | 0.02 | 0.30  | 0.03     | 1.05  | 0.26     |
| 20      | ...    | 22.00 | 0.03 | 0.91  | 0.04     | 2.48  | 0.13     |
| 21      | ...    | 22.75 | 0.18 | 0.90  | 0.21     | 2.73  | 0.25     |
| 22      | ...    | 22.98 | 0.03 | 0.42  | 0.04     | ...   | ...      |
| 23      | ...    | 22.48 | 0.06 | 0.53  | 0.08     | ...   | ...      |
| 24      | ...    | 22.68 | 0.03 | 0.23  | 0.04     | ...   | ...      |
| 25      | ...    | 23.31 | 0.03 | 0.53  | 0.04     | 1.51  | 0.20     |
| 26      | ...    | 22.82 | 0.03 | 0.16  | 0.04     | 0.44  | 0.80     |
| 27      | ...    | 22.92 | 0.03 | 0.28  | 0.04     | 1.53  | 0.25     |
| 28      | ...    | 23.50 | 0.15 | 0.28  | 0.22     | 0.78  | 0.55     |
| 29      | ...    | 23.50 | 0.05 | 0.19  | 0.05     | 2.66  | 0.31     |
| 30      | ...    | 22.94 | 0.04 | 0.12  | 0.06     | ...   | ...      |
| 31      | ...    | 22.99 | 0.05 | 0.15  | 0.06     | 0.87  | 0.57     |
| 32      | ...    | 23.11 | 0.04 | 0.17  | 0.06     | ...   | ...      |
| 33      | ...    | 23.11 | 0.05 | 0.27  | 0.07     | 0.71  | 0.31     |
| 34      | ...    | 23.19 | 0.05 | 0.20  | 0.07     | 0.87  | 0.36     |
| 35      | ...    | 23.83 | 0.07 | 0.92  | 0.08     | 2.00  | 0.29     |
| 36      | ...    | 23.31 | 0.05 | 0.12  | 0.07     | 0.55  | 0.80     |
| 37      | ...    | 23.68 | 0.05 | 0.30  | 0.06     | ...   | ...      |
| 38      | ...    | 24.00 | 0.11 | 0.26  | 0.33     | 1.87  | 0.29     |
| 39      | ...    | 23.71 | 0.06 | 0.14  | 0.08     | 1.47  | 0.11     |
| 40      | ...    | 23.46 | 0.05 | 0.30  | 0.06     | ...   | ...      |

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The resulting object lists were then checked visually on the image display to exclude the very few remaining obvious bright stars and background galaxies. At this stage, our candidate GC list contained 292 sources from all four chips (excluding the central 9 arcsec of the PC chip). A colour−magnitude diagram is shown in Fig. 6. We have adopted selection cuts of $0.5 < B − R < 2.0$ and $B < 27$. The colour cuts correspond to the full range expected.
of GCs older than 1 Myr (Bruzual & Charlot 1993). The faint magnitude limit was chosen to avoid any colour bias in our sample. Within these selection criteria we have 239 objects, the vast bulk of which will be bona fide GCs (as our contamination rate is 5 per cent).

A histogram of $B - R$ colour is shown in Fig. 7. The GCs have an average colour of $B - R \approx 0.66 \pm 0.03$ (error on the mean). The spread in colour is consistent with photometric errors, suggesting that the PGCs are close to a single age and metallicity population. This mean value is shown on the evolutionary tracks of Bruzual & Charlot (1993) in Fig. 8. From $B - R$ colour alone the GCs may have several possible ages, but from our $K$-band imaging above it is clear that the correct age is $\approx 5$ Myr. Thus the majority of detected objects in our deep HST images are PGCs.

Have we detected any GCs from the progenitor galaxies? Milky Way GCs have a mean $B$-band luminosity function that is roughly Gaussian with a peak at $M_B \approx -6.6$, with the brightest GC (ω Cen) having $M_B = -10.7$. These correspond to $B = 26.85$ and 22.75 respectively, at the distance of NGC 3597. Uncertainty in the distance makes these magnitudes uncertain by about $\pm 0.2$ mag. Milky Way GCs have an average extinction-corrected colour of $(B - R)_0 \approx 1.2$. Examination of the colour–magnitude diagram reveals 32 GCs in the expected colour and magnitude range (shaded region in Fig. 6), although perhaps half of these will simply be PGCs with apparently red $B - R$ colours due to photometric errors. If we assume that, say, 20 are truly old GCs, then we can crudely estimate the total population of progenitor GCs. The HST images cover about half of the area out to a galactocentric radius of 125 arcsec, suggesting 40 GCs within this radius. Our HST data only reach to $B = 26.5$, which is slightly less than the expected peak at $B = 26.85$. This suggests that we are sampling about 40 per cent of the GC population in magnitude terms. Thus another correction of $\approx 2.5\times$ is required, giving a total old GC population of about 100. This crude calculation could easily be in error by a factor of 2, but it is not vastly different to the halo GC population of the Milky Way (i.e., $\approx 120$). Unfortunately, such a calculation does not constrain the progenitor types. Deeper $B$-band observations, over a somewhat wider field of view, would provide better constraints on the original GC systems.
GC luminosity functions in old ellipticals show a Gaussian log-normal distribution, with a peak, or turnover, magnitude and fewer GCs at low luminosity (mass). However, for the PGC systems studied to date the luminosity function does not peak, but continues as a power law down to low luminosities. Published slopes include $-1.78$ (NGC 4038/9; Whitmore & Schweizer 1995), $-2.1$ (NGC 3921; Schweizer et al. 1996), $-1.84$ (NGC 7252; Miller et al. 1997) and $-1.8$ (Zepf et al. 1999). For the closer systems, the PGCs in the PC chip are marginally resolved, giving sizes consistent with GCs rather than open clusters (which also have a power-law distribution). Recently, Carlson et al. (1998) have examined the luminosity function for NGC 3597. They found a slope of $-2.0$ to be a reasonable representation. Here, using the same $HST$ data, we also probe the $R$-band luminosity function.

Before probing the GC luminosity, we need to estimate the incompleteness of our $R$-band detections. This was achieved by simulating GCs using the addstar task, and measuring the detected fraction as a function of $R$-band magnitude. An actual WFC chip was used to reproduce the correct noise characteristics. Care was taken to avoid any blending of artificial GCs. The resulting completeness function for the WFC chips is shown in Fig. 9. Our 50 per cent incompleteness level is at $R \sim 26.8$. In Fig. 10 we show the $R$-band luminosity function in log–log space, for the three WFC chips and corrected for incompleteness. It is very similar to that shown in fig. 10 of Carlson et al. (1998). A Milky Way-like GC system with a peak magnitude of $M_R = -8$, would have an apparent magnitude of $R \sim 25.5$ at the distance of NGC 3597, and be an additional 5.5 magnitudes brighter if it was 5 Myr old instead of 12 Gyr old (assuming a solar-metallicity population). This gives an expected peak of $R \sim 20$, with the faint (lower mass) limit of $R \sim 23$. By contrast, the observed PGC luminosity function continues to rise to faint magnitudes ($R \sim 28$) with a power-law-like slope of around $-2$. At the faint end of our luminosity function, assuming a Salpeter IMF, derived masses correspond to $\sim 200 M_\odot$. At 8 magnitudes fainter than the expected peak, these data probe deeper than any previously published study of PGCs. We note that similar mass calculations by Carlson et al. assumed an age of $\sim 500$ Myr, which means that their masses are overestimates. Thus, like other merging galaxies, the low-mass PGCs in NGC 3597 must be destroyed (e.g., by tidal disruption or evaporation) over time if their luminosity functions are to resemble those of old ellipticals (see Zepf et al. 1999).

Elmegreen & Efremov (1997) have proposed that a universal mechanism exists for GC formation. In their model, GCs form in high-pressure regions with an assumed power-law mass distribution of slope $\sim -2$. They suggest that a GC system is formed initially without a characteristic mass, but as low-mass GCs are destroyed over time a characteristic mass develops. Over $\sim 10$ Gyr, the luminosity function grows to resemble that of the Milky Way GC system, with a characteristic mass corresponding to $M_R \sim -8.0$.

In our $K$ image there are many unresolved sources beyond the central $\sim 20$ arcsec (i.e., the region covered by Holtzman et al. 1996). We used daofind to find all sources $3\sigma$ above the background noise. After rejecting three obvious bright stars, one galaxy and objects fainter than with $K = 23$, we were left with a list of 142 candidate PGCs. These objects are listed in Table 4, along with their $K$ magnitudes and photometric errors. Some of the brighter objects will be foreground stars, and some will be compact background galaxies. Indeed, after examining the area in common with the deep $HST$ images, we have excluded a further three stars and two galaxies (as noted in Table 4). As the $HST$ images do not cover the whole area of our $K$ image, we are unable to confidently remove all stars and galaxies. In the absence of overlapping $HST$ data (or optical magnitudes), it is difficult to make conclusive statements about these outer objects, but many will be PGCs.
4 CONCLUDING REMARKS

The combination of near-infrared and optical imaging from the NTT and HST telescopes has provided new insights into the merging system NGC 3597. For the host galaxy we confirm an $r^{1/4}$-like surface brightness profile in the outer regions, and discover the presence of two closely separated ($\Delta r \sim 0.9\,\text{kpc}$) nuclei. The two nuclei seen in our $K$-band image correspond to those seen at radio wavelengths, and are probably the nuclei of the progenitor galaxies at the final stages of coalescence. Various properties of the galaxy starburst suggest that the burst occurred less than 10 Myr ago and may have involved at least one early-type spiral.

A number of protoglobular clusters (PGCs) are identified in NGC 3597, with average colours of $V-K$ = 0.95. The extra leverage provided by our $K$-band photometry allows us to derive a unique age for the PGCs of a few Myr. From deep $B$ and $R$ HST imaging we detect ~300 globular clusters, the vast bulk of which are PGCs. We derive an $R$-band luminosity function which reaches 8 magnitudes fainter than the expected characteristic mass of a standard old globular cluster luminosity function, and confirm the slope of the luminosity function to be about $-2.1$. A small number of globular clusters have properties consistent with Galactic ones, and we speculate that they were associated with the progenitor galaxies.

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