Star formation in the outer filaments of NGC 1275

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ABSTRACT
We present photometry of the outer star clusters in NGC 1275, the brightest galaxy in the Perseus cluster. The observations were taken using the Hubble Space Telescope Advanced Camera for Surveys. We focus on two stellar regions in the south and south-east, far from the nucleus of the low-velocity system (∼22 kpc). These regions of extended star formation trace the Hα filaments, drawn out by rising radio bubbles. In both regions, bimodal distributions of colour (B − R)0 against magnitude are apparent, suggesting two populations of star clusters with different ages; most of the Hα filaments show no detectable star formation. The younger, bluer population is found to be concentrated along the filaments while the older population is dispersed evenly about the galaxy. We construct colour–magnitude diagrams and derive ages of at most 108 years for the younger population, a factor of 10 younger than the young population of star clusters in the inner regions of NGC 1275. We conclude that a formation mechanism or event different to that for the young inner population is needed to explain the outer star clusters and suggest that formation from the filaments, triggered by a buoyant radio bubble rising either above or below these filaments, is the most likely mechanism.

Key words: galaxies: clusters: individual: Perseus – cooling flows – galaxies: individual: NGC 1275 – galaxies: star clusters.

1 INTRODUCTION

Brightest cluster galaxies (BCGs), the most massive galaxies known, offer the opportunity to observe the heating and cooling processes in the intracluster medium (ICM) and provide the ideal environment to test theories of massive galaxy formation.

Optical line-emitting nebulae surround about a third of all BCGs and are found specifically in those where the cluster exhibits a strongly peaked X-ray surface brightness profile and a cool, high-density core, so-called, ‘cool core’ clusters (see Crawford 2004 for a discussion of the optical properties of these clusters). The mass of cool gas implied by the high X-ray luminosity (i.e. the energy-loss rate of the gas) in the centre of cool core clusters is 10 or more times the mass inferred from soft X-rays (<1 keV), observed star formation rates and the mass of cold gas present (Peterson & Fabian 2006). In order for the hot gas to be radiating but not cooling in the predicted quantities, there must be a source of heat regulating the production of cool gas. Energy arguments favour feedback from a supermassive black hole (SMBH), situated in the central galaxy, as the dominant heating process in these clusters (for a review, see Peterson & Fabian 2006; McNamara & Nulsen 2007). Understanding the role the black hole plays with respect to the galaxy’s environment, such as its connection with star formation, is a key question in galaxy evolution.

NGC 1275 is the BCG in the nearby (z = 0.0176) Perseus cluster, the X-ray brightest, cool core cluster. The NGC 1275 system is very complex; Minkowski (1955) discovered that it consists of two galaxies, a high-velocity system (HVS; 8200 km s−1) and a low-velocity system (LVS; 5200 km s−1). 21 cm observations, line absorption in H I and Lyα and continuum absorption in X-rays (Ekers, van der Hulst & Miley 1976; Briggs, Snijders & Boksenberg 1982; Fabian et al. 2000; Gillmon, Sanders & Fabian 2004) show the HVS to lie in front of the LVS. The HVS can be clearly seen in Fig. 1, north-west of the centre.

Early observations showed a spatial correspondence between the HVS and LVS (Hu et al. 1983; Unger et al. 1990) and evidence for gas at intermediate velocities (Ferruit et al. 1997), which led to the suggestion that the galaxies were in the process of merging. However, these observations can also be explained by influences of the ICM (Fabian & Nulsen 1984; Boroson 1990; Caulet et al. 1992)

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or by a past interaction, of one of the systems, with a third gas-rich galaxy (Holtzman et al. 1992; Conselice, Gallagher & Wyse 2001). By examining the X-ray absorption, Gillmon et al. (2004) were able to put a lower limit on the distance between the HVS and the nucleus of the LVS, of 57 kpc. This analysis was repeated with a deeper study by Sanders & Fabian (2007), giving an improved lower limit on the distance between the two galaxies as 110 kpc. This large separation and lack of obvious shocked gas suggest that any interaction between these two systems lies in their future not in their past.

NGC 1275 exhibits interesting optical features in both its relatively blue central colours (Holtzman et al. 1992), indicating the presence of massive, short-lived stars and in its vast extended emission-line nebulae (Minkowski 1957; Lynds 1970) stretching out predominantly radially from the nucleus of the LVS. Large quantities of molecular hydrogen and CO gas have been found in the nuclear region (Lazareff et al. 1989; Inoue et al. 1996; Donahue et al. 2000) and recently detected in the outer Hα filaments (Hatch et al. 2005; Lim, Ao & Dinh-V-Trung 2008; Salomé et al. 2008a; Ho, Lim & Dinh-V-Trung 2009). Soft X-ray emission has also been found to be associated with some of the optical emission nebulae (Fabian et al. 2003); however, it is less luminous than the optical and ultraviolet emission.

Kent & Sargent (1979) found the low-resolution spectra of the Hα filaments to be similar to those of H II regions and well explained by collisional ionization or photoionization from the Seyfert nucleus. Their observations supported a hypothesis that the filaments were formed by an accretion flow on to the LVS. It has since been shown,
with higher resolution spectra, that the galaxy nucleus is not the ionization source (Johnstone & Fabian 1988). Heckman et al. (1989) observed both the filaments in NGC 1275 and broadened their study to include filamentary systems in other BCGs. They found evidence confirming the association of optical emission-line nebulae and cooling flows and discuss mechanisms for heating and ionizing these nebulae.

The central star cluster population in NGC 1275 has been well studied; Shields, Filippenko & Basri (1990) detected Hα regions and excess blue continuum in the central filaments of NGC 1275 which they interpreted as implying the presence of massive young star clusters. Soon after, Holtzman et al. (1992) discovered a population of compact massive blue star clusters in the core of NGC 1275 with the Hubble Space Telescope (HST) Wide Field Planetary Camera 1 (WFPC1). The observed sizes and luminosities led the authors to conclude that these were most likely protoglobular clusters. The conclusion was supported by Richer et al. (1993) using observations from the Canada–France–Hawaii Telescope (CFHT) and by Carlson et al. (1998) using HST WFFPC2 observations. Assuming a Salpeter initial mass function (IMF), previous ages of the central clusters are suggested to be between 10⁴ and 10⁷ years resulting in masses between 2 × 10^⁵ and 10^⁹ M☉.

A further study of the colour distribution of the NGC 1275 system was carried out by McNamara, O’Connell & Sarazin (1996). The $U - B$ colours indicate a centrally concentrated young population and a more diffuse older background population. The young population colours are consistent with ages up to 1 Gyr. Measuring the physical parameters of star clusters in cD galaxies can allow us to constrain both their rate of formation and the underlying physical processes behind their development.

The complicated nature of the NGC 1275 system makes it difficult to determine whether the star cluster populations in the centre lie in the LVS or HVS. Keel & White (2001) suggested that the correlated spatial distribution of the blue clusters and the HVS dust lanes are evidence of this cluster population being part of the foreground HVS. However, Brodie et al. (1998) have shown that at least some of the blue clusters are at the same redshift ($\sim$5200 km s⁻¹) as the LVS. The colours of the blue population have been determined to be similar, regardless of whether the individual clusters have been confirmed to lie in the LVS or are perhaps, spatially, more likely to lie in the HVS (Holtzman et al. 1992; Norgaard-Nielsen et al. 1993; Richer et al. 1993; Carlson et al. 1998). Dixon, Davidsen & Ferguson (1996) observed NGC 1275 with the Hopkins Ultraviolet Telescope and found evidence for a star formation rate of 30 M⊙ yr⁻¹ at the redshift of the HVS.

There are two major competing scenarios for the formation of globular clusters (GCs) in elliptical galaxies. Ashman & Zepf (1992) propose that elliptical galaxies form through mergers which trigger the GC formation, while Forbes, Brodie & Grillmair (1997) propose that the GCs form ‘in situ’ via collapse into a single potential well (for a review, see Brodie & Strader 2006). The merger scenario produces a bimodal distribution of clusters and is supported by the observation that elliptical galaxies tend to have a higher specific frequency (number of clusters per unit galaxy light) than spiral galaxies. The formation processes of the clusters in the centre of NGC 1275 are discussed by Carlson et al. (1998) and Richer et al. (1993). The former prefer a model where the star formation is triggered by a merger while the latter suggest that the star formation is due to cool gas collected at the centre of the cooling flow. The main contention is whether the colour–magnitude diagram shows evidence of a single-age population or of a continuously forming population of star clusters.

Ferruit & Pecontal (1994) used TIGER, an integral field spectrograph (IFS) mounted on the 3.6-m CFHT to detect emission-line regions coincident with the central clusters, previously assumed only continuum sources. These regions exhibit spectral features very different to the Hα regions discovered previously and have spectral and kinematical properties characteristic of the filaments. The line ratios suggest that photoionization by the star clusters cannot account for the gas ionization in the filaments. These findings, coupled with the uncertainties of our knowledge of the internal reddening in NGC 1275, led the authors to support the theory that the clusters were formed from a cooling flow.

Further IFS observations with GMOS on Gemini were taken by Trancho et al. (2006). These observations confirmed the discovery of emission lines associated with some star clusters, although the majority exhibit very little gas emission.

The star formation is however not limited to the central region (see regions marked in Fig. 1). NGC 1275 also exhibits regions of much extended star formation noted by Sandage (1971). The ‘blue knots’ of Sandage (1971) form the eastern side of the Blue Loop, approximately 22 kpc to the south-east of the nucleus (Fig. 1). Conselice et al. (2001) presented colours and magnitudes for clusters near the north-west of the HVS and a few bright clusters on the eastern arm of the Blue Loop. On the Blue Loop, they measure very blue colours with $(B - R)_{0} \approx -0.3$ to $0.0$.

These objects can be dated from their colour–magnitude relationships and through this we can examine their relationship to the Hα filaments and to the wider cooling and heating flows in the galaxy. Observations of cooling flows and star formation in BCGs can give us an insight into the evolutionary cycle that the gas undergoes in these objects.

In this paper, we present observations, obtained with the HST Advanced Camera for Surveys (ACS) spanning an area of approximately 5.5 arcmin². The observations allow us to analyse the star formation spatially coincident with the Hα emission-line filaments in the outer regions of the system. The regions are too far from the centre of NGC 1275 to be seen on the WFPC2 images of Carlson et al. (1998). In Section 2 we discuss the observations and data reduction procedure, and in Section 3 we present the results of the analysis and highlight potential sources of error. We discuss the results in the context of different formation scenarios of the extended star formation in Section 4 and conclude in Section 5.

2 Observations and Data Reduction

Observations were made using the HST ACS on 2006 August 5 in the F435W, F550M and F625W filters (Fabian et al. 2008). Total exposure times were 9834, 12132 and 12405 s, respectively.

The F625W filter includes Hα, [N ii] and [S ii] emission from both the HVS and the LVS. This differs from the Conselice et al. (2001) ground-based, narrow-band imaging that excluded the HVS. The standard procedure was used to bias-subtract and flat-field the data frames which were then drizzled together as described in the HST ACS data handbook.

Fig. 1 shows the ACS F435W filter image of NGC 1275 combined with a red image made by subtracting the scaled F550M image from the broad-band F625W filter, removing the contribution from the galactic continuum. Here the relation between the star formation and the line emission nebulae can be seen clearly. The HVS is in the line of sight of the nucleus of the LVS and appears to have a backward S-shaped configuration. Fig. 2 shows the relationship between the Hα filament and the star clusters in the Blue Loop region more clearly. Here it can be seen that on the western arm
the clusters are spatially offset from the filament by approximately 10 arcsec corresponding to a distance of 3.5 kpc at a redshift of \( z = 0.0176 \) (we adopt \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \)). Clusters on the eastern arm coincide directly (in the line of sight) with the \( \text{H} \alpha \) region are more compact than the clusters in the centre. The point-spread function fitting technique for crowded fields employed by IRAF DAOFIND was not used as many of the clusters are partially resolved, and we required that a single technique should be used for the whole field. As in Carlson et al. (1998), we required the DAOFIND parameters of roundness between −1 and 1 and sharpness between 0.2 and 1. In the central image, only the south-west region was considered; it is both less obviously 'dusty' and allows a more direct comparison of our colour–magnitude results with previous results.

IRAF PHOT was employed to perform aperture photometry using an aperture with a 2 pixel radius in all regions and all filters. The background in the Blue Loop and southern filament region was estimated using the modal value in an annulus 10 pixels wide with an inner radius of 15 pixels. In all regions, growth curves of the brightest, isolated star clusters in the field were constructed to test the background estimation. The galaxy background near the outer regions of star formation, far from the nucleus, does not vary much with position; however, the field here is crowded. The large inner radius of the background annulus ensures we are sampling much more background than surrounding stars. In the central region, an inner radius of 12 pixels and annulus 2 pixels wide, as in Carlson et al. (1998), was found sufficient to estimate the background. The small sky radius here is used to minimize the variation of the background due to the galaxy. No subtraction of the smooth galaxy light in the inner region was done as the error introduced in the bright sources of interest is small. The worst case scenario of a non-linear background variation over the 28 pixels for the innermost cluster introduces an error of less than 0.3 counts s\(^{-1}\). The variation of background to peak for this innermost cluster is less than 2 per cent. In the inner region, the bright galaxy nucleus was masked out, as was a bright saturated star near the top of the eastern arm of the Blue Loop.

Average aperture corrections are determined using the 10 brightest sources in each of the three regions. These are corrections from a 2 pixel radius aperture corresponding to a 0.1 arcsec radius aperture flux to a flux determined with a 0.6 arcsec radius. These corrections are listed in Table 1. The corrections are similar but slightly larger than those found by Carlson et al. (1998) in the core of the galaxy. The aperture correction for the three stellar regions was determined separately and is found to be marginally larger in the outer regions. The point spread function changes with position on the chip (errors of a few per cent), due to both optical aberrations and geometric distortions which may be responsible for the small differences detected in aperture correction across the field.

Our colour–magnitude results for the three regions are shown in Figs 3 and 4. Fig. 5 shows a colour–magnitude plot of the outer star formation regions accompanied by photometry of neighbouring control regions. We do not find any objects as blue as our blue population of clusters in any of these fields; however, the red population appears ubiquitous throughout the field. Contamination of the young star cluster population from foreground and background sources is therefore highly improbable due to both the lack of young blue sources in other regions and the spatial distribution of the blue population in the Blue Loop and southern filament regions. This is discussed further in Section 3.1 and Fig. 7.

The ACS filters differ significantly from other filter systems, and this needs to be taken into account when determining reddening corrections from the galactic foreground. Due to the differences in filter transmission curves between ground-based and the ACS filter systems, the extinction coefficients are calculated in the native photometric system and all corrections applied before converting to another system.

For comparison with the stellar evolutionary synthesis models, we transform the ACS filter system to the Johnson–Cousins \( UBVRI \) system using the method below, described in Holtzman et al. (1995) and Sirianni et al. (2005).

\[
TMAG = SMAG + c_0 + c_1 \times TCOL + c_2 \times TCOL^2.
\] (1)

The F435W filter can be transformed to a \( B \)-band filter and F625W to a \( R \)-band filter; however, uncertainties of a few per cent are introduced during this transformation. An additional systematic error is introduced when using the synthetic transformation coefficients for stars with \( B - V < 0.5 \) due to uncertainties in the shape of the total response curve in the F435W filter (see Sirianni et al. 2005, their fig. 21). The overall uncertainty in these transformations is of
Figure 3. Vega magnitude (F435W) against colour (F435W − F625W) for the three regions. All data points have errors in single passbands less than 0.15 mag. Top panel (a) shows the Blue Loop region (RA 03°19′52"1, Dec. 41°30′08″6 J2000), panel (b) the southern filament (RA 03°19′46″5, Dec. 41°30′04″5 J2000) and panel (c) the south-west section (RA 03°19′47″9, Dec. 41°30′38″8 J2000) of the nucleus. The blue and red lines in panels (a) and (b) indicate the mean colours of the blue and red populations, respectively. The blue and red populations are determined by inspection of the histogram (see Fig. 4). The lines in panel (c) show the average colours determined by Carlson et al. (1998) for their blue and red populations, in the same region.

The level 5–10 per cent. For comparison, Fig. 6 shows the $B$-band magnitude versus colour diagram for the clusters after conversion to the Johnson–Cousins system. We used the synthetic transformation coefficients given in appendix D, table 22 in Sirianni et al. (2005) as these cover the larger colour range necessary for these results. We required the convergence criterion to be $1 \times 10^{-5}$.

The extinction coefficients are determined by a constant times the reddening,

$$\frac{A_\lambda}{E(\lambda - V)} = R_\lambda.$$  \hspace{1cm} (2)

Here we have assumed that the constant, the ratio of total to selective extinction, is $R_B = 3.1$ (Pei 1992). This is the standard value derived from the $(B - V)_0$ colours in the Johnson–Cousins $UBVRI$ band-passes, using a ground-based system. The extinction ratios in the ACS filters were derived by Sirianni et al. (2005) using the Cardelli, Clayton & Mathis (1989) Galactic extinction law. The throughput

\[^1\] The $0$ notation used for magnitudes and colours in this paper refers to corrections for foreground Galactic extinction only.
Figure 4. Left-hand panel: the extinction-corrected colour–magnitude diagram for the Blue Loop. Right-hand panel: the number of clusters, in this region, detected in colour bins of width 0.1 mag. Here the bimodal distribution of colours can be clearly seen. The blue population (lower) has a broader distribution than the red population (upper); it also appears to have a tail towards the red end. The cut-off between the two populations lies at $(F435W - F625W)_0 \sim 0.4$. The mean colour of the young, blue population is $(F435W - F625W)_0 = -0.22$.

Figure 5. Colour–magnitude diagram showing a comparison of the results for the Blue Loop and southern filament regions (in black) and for two control regions (in red) of size $15 \times 15$ arcsec$^2$ taken next to these regions.

in the medium and broad-band filters depends on the colour of the object. Sirianni et al. (2005) selected three template stars (05 V, G2 V and M0 V) from the Bruzual–Persson–Gunn–Stryker atlas of which we have adopted the 05 V results to compute the extinction coefficients in the three filters (Table 2). The results are normalized to the value $R_B = 3.1$; however, there are systematic differences in extinction between the ACS system and a ground-based system as a function of $E(B - V)$ due to differences in effective wavelength. The extinction in our ACS wide-band filters is systematically higher than in the $U$, $B$ and $V$ bands as the effective wavelength is shorter. In the F814W band, the effective wavelength is longer and so the

Figure 6. Johnson–Cousins $(B - R)_0$ colour against $B$-band Vega magnitude diagram for the Blue Loop region.
Table 2. Galactic extinction coefficients for each ACS passband used.

| Filter | Extinction coefficient |
|--------|------------------------|
| F435W  | $A_{F435W} = 0.67$     |
| F550M  | $A_{F550M} = 0.50$     |
| F625W  | $A_{F625W} = 0.43$     |

extinction here is systematically lower than in the $I$ band (Sirianni et al. 2005). The value for reddening in the direction of NGC 1275 we use is $E(B - V) = 0.1627 \pm 0.0014$ determined using the Galactic reddening maps of Schlegel, Finkbeiner & Davis (1998).

There will also be reddening from the dust in NGC 1275 itself. This will cause a greater effect towards the centre of the galaxy, especially near the HVS, resulting in the measurement of redder colours. The internal extinction is difficult to constrain; however, the two main areas of interest in this work, the Blue Loop and the Southern filament, are far from the dust lanes (Keel & White 2001), so we have not attempted to add a correction for this effect.

3 ANALYSIS AND RESULTS

The H$\alpha$ filaments belonging to both the LVS and HVS have been investigated by Conselice et al. (2001) (their fig. 2), and Caulet et al. (1992) (their fig. 2), respectively. Their images show the extended filamentary system is predominantly associated with the large central galaxy not the smaller high-velocity galaxy in the line of sight. Hatch et al. (2006) identify a 1-arcmin-long chain of blue star clusters in the north-west of NGC 1275 (RA 03$^h$19$^m$46$^s$, Dec. 41$^\circ$31'45''J2000), an extension of those mentioned by Conselice et al. (2001). Only one blue knot within this chain appears to be spatially connected with the H$\alpha$ filaments. Hatch et al. (2006) find that this blue knot has a line-of-sight velocity of 5538 km s$^{-1}$, placing it within the LVS.

The following analysis assumes that the star clusters along the two extended regions of star formation studied here also belong to the LVS (also see later discussion at the end of Section 4 and Fig. 14). Future spectroscopic data of these star clusters would allow us to place the clusters firmly within the HVS or LVS.

3.1 Spatial distribution of clusters

The clusters in the south-west region contain a range of colours evenly distributed about the core of the galaxy, implying that the old and young population is interdispersed throughout the core of the LVS. The south-west region is spatially the most distinct region from the HVS in the core of NGC 1275; however, confusion with this system cannot be ruled out.

In the Blue Loop region, all ‘bluer’ clusters [defined as those with de-reddened $(F435W - F625W)_0 < 0.4$] are found to lie along the loop, which coincides with the H$\alpha$ emission (see Fig. 7). The ‘redder’ clusters [de-reddened $(F435W - F625W)_0 > 0.4$] are evenly distributed and have the same colours as clusters found in a control region of the galaxy at a similar radius. The control region used has a central RA 03$^h$19$^m$54$^s$ and Dec. 41$^\circ$30'37''/7(J2000) and was 10 by 10 arcsec across. This is also found to be the case in the southern filament region, here blue clusters have $(F435W - F625W)_0 < 0.5$ and red clusters have $(F435W - F625W)_0 > 0.5$. Projection effects make it difficult to be precise about the arrangement of the extended filamentary systems in NGC 1275; however, the close nature of the filaments and the stellar regions, and the fact that we see this apparent association in more than one area, yet the filaments themselves are very sparse in the extended regions, suggest that the star formation is likely to be intimately linked to the optically emitting filaments.
3.2 Stellar population models

We use simple stellar populations (SSP) models to estimate the ages of the young populations of clusters. It is likely that these clusters formed almost simultaneously and with similar metallicities, allowing them to be described by these models.

The commonly used models of Bruzual & Charlot (2003, hereafter BC03) and the GALEV evolutionary synthesis models (Kotulla et al. 2009) have been used to determine an upper bound on the ages of the star clusters in NGC 1275. The GALEV models have the advantage of including the ACS filter system while the BC03 models require a photometric transformation to the Johnson–Cousins UBVRI system. This transformation introduces errors of a few per cent (Sirianni et al. 2005). The GALEV SSP models are shown for a range of metallicities and IMFs $[\Phi(m)\alpha]$ in Figs 8 and 9. These are all computed using the Padova (1994) isochrone models. Kotulla et al. (2009) assume a lower mass cut-off of $m_L = 0.1 \, M_\odot$ while they allow the upper mass cut-off to depend on metallicity. A cut-off of $m_U = 50 \, M_\odot$ is assumed for supersolar metallicity and $m_U = 70 \, M_\odot$ otherwise. The Salpeter, Scalo and Kroupa IMFs assumed are defined with $\alpha$ given in equations (3)–(5), respectively,

$$\alpha = -2.35$$

$$\alpha = \begin{cases} 
-1.25 & \text{if } m \leq 1 \, M_\odot \\
-2.35 & \text{if } 1 \, M_\odot < m \leq 2 \, M_\odot \\
-1.25 & \text{if } 0.5 \, M_\odot < m
\end{cases}$$

$$\alpha = \begin{cases} 
-1.30 & \text{if } m \leq 0.5 \, M_\odot \\
-2.30 & \text{if } 0.5 \, M_\odot < m
\end{cases}$$

The BC03 SSP models (Fig. 10) are computed assuming a Salpeter IMF and the Padova (1994) evolutionary tracks. The models assume an IMF with a low-mass cut-off of $m_L = 0.1 \, M_\odot$ and a high-mass cut-off of $m_U = 100 \, M_\odot$. The models are normalized to a total mass of $1 \, M_\odot$ in stars at age $t = 0$.

Figure 8. (F435W – F625W)$_0$ colour versus age relationship for several metallicities, measured relative to solar, using the GALEV SSP models, assuming a Salpeter IMF with lower mass cut-off $m_L = 0.1 \, M_\odot$. The upper mass cut-off depends on metallicity with $m_U = 50 \, M_\odot$ for supersolar and $m_U = 70 \, M_\odot$ otherwise. The hashed lines show the spread in colour of the young, blue population in the Blue Loop region.

Figure 9. The (F435W – F625W)$_0$ colour versus age relationship using GALEV SSP models assuming solar metallicity with a Kroupa, Salpeter and Scalo IMF, respectively.

Figure 10. Johnson–Cousins ($B - R$)$_0$ colour versus age relationships for three different metallicities using BC03 models for a single-age, single-burst population and assuming a Salpeter IMF. Lower and upper mass cut-offs are assumed to be $m_L = 0.1 \, M_\odot$ and $m_U = 100 \, M_\odot$, respectively. The hashed lines show the spread in colour of the young, blue population in the Blue Loop region.

X-ray observations have shown the metallicity of the ICM to be approximately 0.6 of solar abundances at the Blue Loop region (Sanders et al. 2004; Sanders & Fabian 2007). Given this, metallicity abundances as high as twice solar or higher ($Z = 0.05$), in these stars, are very unlikely as are abundances as low as 2 per cent ($Z = 0.0004$) solar (Fig. 8). We might expect differences in the metallicities of the old and young cluster populations, the old clusters are potentially metal-poor globulars while the young clusters are likely to have metallicities $\sim$ solar. The SSP models used agree well for ages larger than $10^7$ years; however, modelling very young stars is complex and
the models remain uncertain. This, coupled with errors on the data, makes it impossible to constrain the metallicities of the regions.

The observed colour of the clusters is highly sensitive to age, metallicity, dust extinction and the coincidence of the clusters with Hα filaments. Older, metal-rich, dusty populations will appear redder. The star formation in regions such as the Blue Loop is far from the nucleus (∼22 kpc) and exhibits no obvious signs of dust, so internal reddening is unlikely to have a large effect. As discussed above, the metallicities are likely to be ∼ solar; however, as seen in Figs 8 and 10, changes in metallicity can have a significant effect on the colour of young stellar populations. The clusters in our sample are coincident with Hα emission. This will have the effect of reddening the colours of these clusters and may make them appear older than they are if the emission is within the photometry aperture or make them appear bluer if the emission is within the background annulus. There are twice as many counts in the brightest filamentary regions on the Blue Loop than counts in the background and for fairly bright sources (25 mag) the background counts are only 2 per cent of the counts from the cluster. To make a 10 per cent difference to the (F3435W − F625W)0 colour, the Hα ([NII]) emission would require an equivalent width of > 100 Å. This is very large and unlikely to be an issue.

3.2.1 Blue Loop

The bimodal distribution in colour shown in Fig. 4 strongly argues for a two-age population of clusters in this region. The colours of the ‘bluer’ region are very blue with an average, extinction corrected colour of (F3435W − F625W)0 = −0.2, much bluer than the protoglobular clusters found in the core of the system (∼0.3). This also argues for a low internal extinction in this region.

Assuming a metallicity of Z = 0.02 (≈ Z⊙) for the star clusters and a colour range between −0.4 and 0.2, lower and upper age estimates from the BC03 SSP models are 5 × 106 and 5 × 107 years. The GALEV models yield an upper limit of 0.75 × 108 years. The ages and luminosities can also give us estimates of the total mass in the clusters and hence put limits on the star formation rates. We get a lower limit of 9 × 105 M⊙ for all the blue clusters summed together. This provides a limit on the star formation of about 20 M⊙ yr−1 over the whole Blue Loop region. The average mass in the clusters is found to be 4 × 105 M⊙ with the brightest clusters having masses ∼107 M⊙.

In the central region, Carlson et al. (1998) found mass estimates for their brightest clusters of about 107−108 M⊙. These results are highly dependent on the IMF and the models assume a single-burst, single-age population. In the Blue Loop, the relatively large amount of scatter in panel (a) in Fig. 3 suggests, assuming these clusters all share the same metallicity, that it does not have a true single-age population. This could be evidence of continuous star formation which ‘turned on’ approximately 108 years ago, the likely dynamical lifetime of the Hα filaments (Hatch et al. 2005). However, we note that, for very young stellar populations (<106 years), the SSP models are uncertain and the breadth of the colour population may not necessarily translate into a large age difference. A stellar population with an age 108−109 years can span the whole range of observed colours using BC03 models while the GALEV SSP models cannot account for any of the bluest clusters observed.

There is also a large amount of diffuse blue light along the Blue Loop region and particularly on the north-west side towards the galaxy. This is most likely emission from smaller clusters and single stars, possibly tidally stripped, or dissolved from, surrounding larger clusters. If these stars are similar in age to the clusters in the loop, we would expect the total mass in stars, and therefore also the star formation rate calculated, to be a lower limit.

3.2.2 Southern filament

The Southern filament region shows slightly redder colours (F435W − F625W)0 ∼ −0.1–0.2 than the Blue Loop region (F435W − F625W)0 ∼ −0.4–0.1 with a lower and upper limit on the ages of the star clusters of about 8 × 106 and 5 × 108 years from the BC03 models and an upper limit of 5 × 108 years from the GALEV models. Fig. 3 panel (b) shows there is a clear bimodal distribution in this region; however, the distribution of colours in the young blue population is again fairly broad.

3.2.3 South-west nuclear region

The age estimates from the models applied to the south-west portion of the nuclear give limits of 107 and 108 years, in agreement with the values estimated by Carlson et al. (1998) and with the spectroscopically determined ages of five of the brightest inner clusters by Brodie et al. (1998).

3.3 Tidal forces

Fig. 11 shows that there are ‘groups’ of star clusters in the Blue Loop which have a structure reminiscent of a tail. One explanation for this could be that when the stars have formed they are unable to escape the gravitational potential of the galaxy and fall back in towards the nucleus.

If the star clusters have been tidally stripped, we would expect a gradient in the ages of the blue population. The star clusters forming first would have been subject to tidal stripping for longer and so should have fallen further towards the galaxy.

To detect whether there is a discernible age difference across the star cluster ‘groups’ in the bright eastern arm of the Blue Loop, we choose five prominent groups of clusters. These are shown in Fig. 12 and the results of the photometry are given in Table 3. Three of the regions, those with apertures 2/3, 8/7 and 10/9 are found to have the younger, bluer clusters towards the south and two, 1/6 and 4/5, the younger clusters to the north. The difference detected in both 8/7 and 4/5 is small compared with the error in colour. The detected difference in colour in region 1/6 is very large but on closer inspection of the apertures it is not clear that they cover the same group of clusters so this region should be discounted.

Regions 2/3 and 10/9 show a difference in colour larger than the error (change of 0.4 and 0.12 between apertures, respectively). In both the regions, the younger clusters appear to lie in the southernmost aperture. This is expected if the star clusters have formed at different times and not in some rapid event.

The age of the clusters can be estimated by assuming each elongated group to be experiencing tidal stripping as it falls into the nucleus. The groups have an initial angular momentum from the group formation process. The ratio of the length to width (Δs/Δr ≈ 5; see Fig. 11) of each of these groups of clusters can then be measured and the time over which they have been stripped equated with the age by making the assumption that as soon as the gas was able to condense out of the filament and form stars they started to fall into the nucleus. The typical ratio of Δs to Δr is measured from the ACS images; note though that projection effects could significantly alter this ratio.
Equations (6) and (7) assume that the clusters within each of these groups started to form in one place so the spread of the group \((\Delta s \text{ and } \Delta r)\) seen now is the result of the initial velocity of the gas and tidal forces from the attraction of the LVS. The gravitational acceleration felt by the element is \(\Delta g \approx v^2/r\), where \(v = 700 \text{ km s}^{-1}\) is the velocity dispersion. The velocity dispersion is inferred from the temperature of the ICM (Fabian et al. 2006) measured in X-rays. The tidal acceleration is given by \(\Delta g \approx GM/\Delta r^3 r \sim g/\Delta r\),

so after time \(t\)

\[\Delta s \approx \frac{1}{2} v^2 t^2,\]  

\[\Delta r \approx \frac{GM}{v^2} \approx \frac{1}{2} \frac{v^2}{r^2} \Delta t.\]  

The distance from the centre of the potential to the group is \(r = 63\) arcsec which is about 22 kpc at the distance of NGC 1275. With the ratio \(\Delta s/\Delta r \approx 5\) and a velocity dispersion of \(v = 700 \text{ km s}^{-1}\), we calculate an age of \(9 \times 10^7\) years, approximately the same as the upper bound on the estimate from the SSP models. The precise nature of the tidal distortion for either radial or tangential motion depends on \(v(r)\) which in turn depends on the mass distribution.

4 DISCUSSION

In this paper, we present photometry results for star clusters close to the nucleus and at a radius of \(\sim 1\) arcmin in the dominant galaxy in the Perseus cluster, NGC 1275. We give limits on the ages and masses of the star clusters and find a marked difference in the ages of the stars in the outer regions compared to those closer to the nucleus of the galaxy. In this section, we discuss the implications of these results for the formation scenarios of the inner and outer cluster regions in turn.
4.1 Inner stellar regions

Our results, corrected for galactic extinction but uncorrected for internal extinction, yield colours of \((F435W - F625W)_0 \sim 0.2 - 0.6\) for the bluer star cluster population in the centre of NGC 1275. From SSP models, we derive lower and upper limits on the ages of the clusters as \(10^7 - 10^9\) years, respectively, and an upper limit on the mass of the brightest clusters of \(10^8 M_\odot\).

Holtzman et al. (1992) were the first to discuss the formation scenarios of the bimodal population of star clusters in the LVS in NGC 1275. They detected a central population of blue clusters and explored three possible formation processes: (1) an interaction with the HVS; (2) star formation triggered by the cluster cooling flow and (3) star formation from a previous interaction with a third gas-rich galaxy. They rule out (1) primarily due to the high velocity \(3000 \text{ km s}^{-1}\) at which the two systems are falling towards each other and the clusters being roughly symmetrically distributed around the nucleus, rather than having a preferential direction towards the HVS. This conclusion was also reached by Unger et al. (1990). The second scenario was ruled out by the authors on the basis of the observed uniformity of the colour of the young, blue population of clusters. The same grounds favour scenario (3). This latter interpretation is supported by \(HST\) WFPC2 observations made by Carlson et al. (1998). However, Richer et al. (1993) found a broader range in colours with no obvious bimodality in their colour–magnitude diagram, which could indicate a large range in cluster ages and favour a scenario whereby the star formation occurs in a more continuous manner. This is supported spectrally by the work of Ferruit & Pecontal (1994) who found the gas coincident with some of the inner clusters to have spectral properties similar to the gas in the filaments.

Two issues have changed since the earlier work involving scenario (3). The first is that the apparent destruction of the HVS at over \(100 \text{kpc}\) out from NGC 1275 emphasizes that the ICM can prevent gas-rich galaxies penetrating right to the centre. The second is the enormous abundance of molecular gas already at the centre (more than \(5 \times 10^9 M_\odot\), Salomé et al. 2006) which can easily supply fuel for star formation if dragged out by bubbles.

In this work, we find evidence for a bimodal distribution of colours in the star clusters located in the south-west portion of the nucleus. However, we detect a larger scatter about the modal value than that found by Carlson et al. (1998). Difficulties in photometry caused by a highly varying background, uncertain internal extinction and confusion with the HVS do not allow us to conclusively rule out a history of formation by an interaction/merger with another galaxy or a history of extended star formation in the younger, bluer population of clusters in the centre of NGC 1275.

4.2 Outer stellar regions

In both the Blue Loop and the Southern filament, we find much ‘bluer’ colours than in the core, with the former being the ‘bluest’. Colours in the Blue Loop of \((F435W - F625W)_0 \sim 0.4 - 0.1\) and the southern filament of \((F435W - F625W)_0 \sim 0.1 - 0.2\) yield upper limits on the age of the extended star formation of \(5 \times 10^7\) and \(10^8\) years, respectively, a factor of 10 younger than the blue clusters in the central region.

Conselice et al. (2001) found colours on the bright eastern wing of the Blue Loop to be in the range \((B - R)_0 \sim 0.3 - 0.0\) consistent with our results. The very blue colours and the large distance from the nucleus \((\sim 20\text{kpc})\) found here suggest that the internal reddening in this region is small and argues strongly for a two-age population in these regions.

4.3 Star formation scenarios

We consider two formation scenarios for the outer stellar regions: (1) formation related to a previous interaction assumed responsible for the inner stellar populations and (2) a formation scenario entirely independent of the young, inner stellar populations.

4.3.1 Star formation triggered by an assumed previous interaction

For star formation in the extended stellar regions to be triggered by a previous interaction, the young, blue populations should either be coeval or the interaction needs to have had a delayed effect causing the star formation in the inner regions to occur before the outer regions.

If the outer and inner regions of star formation are of the same age, there must be a large amount of internal extinction in the core of the galaxy. Assuming no internal extinction in the Blue Loop, the colour correction needed for this region to be of comparable age to the inner clusters is \(E(B-V) \sim 0.6\). This means that the difference between the \(B\) and \(R\)-band extinctions would need to be three times greater than the extinction calculated here to correct for Galactic reddening along the line of sight to NGC 1275. There is significant internal reddening from the LVS and also from the HVS. Shields et al. (1990) use \(A_V = 1.2\) which gives an \(E(B-V) = 0.39\) using the typical ratio of the extinction to the reddening of 3.1. We minimize the reddening due to the HVS by observing only the south-west, central region that is least obviously connected with the HVS.

The spatial distribution and distance from the core of the extended star formation and the linear nature of the \(H\alpha\) filaments argue against both of these scenarios. A merger or interaction of some kind is unlikely to disturb the Blue Loop and Southern filament systems enough to cause large amounts of localized star formation in these regions without disturbing other filaments nearby. The range of colours, especially in the Blue Loop, is also quite large; this could mean that the population is not all the same age and therefore unlikely to have been formed in some rapid event.

4.3.2 Formation scenarios independent of an assumed previous interaction

The extended blue populations of star clusters are particularly intriguing as they appear spatially distributed along or just offset from some radial \(H\alpha\) filaments but only in certain regions of the galaxy; most \(H\alpha\) filaments are not accompanied by star formation. Another galaxy–galaxy interaction is unlikely to be responsible for
this young population for both the reasons discussed above and due to the very young age of these clusters, the oldest in the Blue Loop being at most $5 \times 10^7$ years.

With the HST images, Fabian et al. (2008) have resolved some filaments into a collection of threads, each of which has a diameter of about 70 pc. They argue that magnetic fields close to the pressure equipartition value of the hot gas, of about $100\mu G$, are required for the thin threads within the filaments to maintain their integrity against tidal forces in the cluster core. Filaments with a higher mean density would not be supportable. The general lack of massive star formation within the filaments is then due to magnetic fields which balance the self-gravity of the cold gas (see McKee et al. 1993 for a review of the role of magnetic fields in star formation and Ho et al. 2009 for a discussion on the inner region of NGC 1275).

Fabian et al. (2008) find that a typical thread has a radius of 35 pc, a length (l) of 6 kpc and a mass of about $10^6 M_{\odot}$ (obtained by scaling the H$\alpha$ emission to a filament complex of total mass, obtained from CO observations of $10^8 M_{\odot}$; Salomé et al. 2008b). The mass of a whole 6 kpc long thread therefore corresponds to the mass of one observed star cluster. The perpendicular column density $N \sim 4 \times 10^{20}$ cm$^{-2}$ or $\Sigma_{\perp} \sim 7 \times 10^{-4}$ g cm$^{-2}$. The lengthwise column density, $\Sigma_{\parallel}$, is $l/2r$ times larger. The critical surface density $\Sigma_c$ for gravitational instability corresponding to the magnetic field inferred in the filaments is given by $\Sigma_c = B/2\sqrt{G} = 0.062(B/100 \mu G) g$ cm$^{-2}$, which is about two orders of magnitude larger than the inferred value for a thread, which is therefore individually very stable against gravitational collapse.

This leaves the question, why is there any star formation at all and why does it only occur in certain places? We can only speculate here but suspect that stars form when and where threads knot and clump together to make much larger structures. There are many examples in the images of NGC 1275 where the filaments appear knotty. If a region is disturbed or stretched in a radial direction, so that the cold gas can accumulate, then clumps which are gravitational unstable can arise and form the star clusters which have been the subject of this work. Examples where gas may be accumulating as the field lines are stretched out are the ends of the horseshoe (for this feature, see figs 13 and 3 of Fabian et al. 2008). There appears to be no star formation there at present but H$\alpha$-bright knots are seen.

Clumps or parts of filaments which are gravitationally unstable have a column density which is much too high to be ‘pinned’ to the surrounding hot gas by magnetic fields and presumably have their own ballistic orbits. The process of star formation might then be dynamical. Threads within the long-lived outer filaments are supported by magnetic fields and are stable to gravitational collapse. When the gas aggregates, they separate from the hot gas and, if sufficiently dense, collapse to form star clusters.

We can put a limit on the maximum mass of a cluster using the arguments of McKee et al. (1993), assuming a steady, poloidal, time-independent magnetic field. Roughly, the magnetic energy scales as $M \sim B^2 R^2$ and the gravitational energy scales as $W \sim M^2/R$; so for a given field, there is a critical mass where the magnetic field can no longer support the filament against gravitational collapse. This mass, $M_B$, for a magnetized cloud of radius $R$ and magnetic field $B$, with a constant of 0.12 determined from numerical calculations allowing for deviations from uniform spherical clouds (Tomisaka, Ikeuchi & Nakamura 1988), is

$$M_B = 0.12 \frac{BR^2}{G^{1/2}}.$$

Taking typical values for a thread, then $BR^2$ is $\pi \times (35 \text{pc})^2 \times 100 \mu G$ remaining in $M_B$ at just under $10^6 M_{\odot}$. This is just less than the average mass of a young cluster in the Blue Loop region of $4 \times 10^6 M_{\odot}$. In order for a thread-sized region to achieve gravitational collapse, its mean density needs to rise by about $10^3$ above what is inferred for a typical thread (Fabian et al. 2008). The cold material therefore needs to aggregate considerably, as discussed above. Note that the mean density of a resolved thread of $\sim 2 \text{cm}^{-3}$ is much lower than the actual density of the cold gas ($\sim 100$–$1000 \text{cm}^{-3}$) if its thermal pressure is comparable to the thermal pressure of the surrounding X-ray emitting gas where $nT \sim 10^6 \text{cm}^{-3} \text{ K}$. (In other words, the volume filling factor of cold gas in a thread is low.)

The brightest star clusters have masses of the order of $10^7 M_{\odot}$. This requires them to originate from regions several times larger than a thread. Since such regions cannot be suspended by the hot gas, then the observed values of the thickness of long-lived threads no longer apply. As mentioned above, one explanation is that the threads knot together and collapse along their lengths, allowing them to evolve from stable to unstable structures over time.

We can only speculate on what has triggered star formation of the Blue Loop. It coincides with a hotter region in the X-ray temperature map (Fig. 14), which is the best evidence that the stars are associated with the LVS and not the HVS. Clear confirmation must await spectroscopic measurements of the star clusters. The blue loop roughly lies diametrically opposite the horseshoe and the outer ghost bubble seen in X-ray maps, which could indicate that the inner jets once went along a NW–SE axis rather than the current almost N–S one (e.g. the jets may precess Dunn, Fabian & Sanders 2006). There is a particularly bright arc of X-ray emission in the SE direction between the Blue Loop and the nucleus, which means the X-ray emitting gas is denser there. If this caused disruption of the jet, then the jet interaction may have been unusual and have led to more cold gas being dragged out or the gas out there having been strongly disturbed. We can find no particular reason why the southern filament shows star formation.
5 CONCLUSIONS

In this paper, we present ACS observations of the extended star formation in NGC 1275, assumed to be associated with the LVS and tracing the spatial distribution of the Hα filamentary system.

We find a bimodal distribution with average colours of $(F435W - F625W)_{0} \sim -0.4$–$0.1$ and $(F435W - F625W)_{0} \sim -0.1$–$0.2$ for the blue population in the Blue Loop and the southern filament, respectively. In the central region, we find much redder colours, consistent with previous results. Assuming SSP models, these very blue colours translate into an age of less than $10^{8}$ years, a factor of 10 younger than the youngest cluster populations in the core. This value is supported by assuming tidal interactions between these star forming regions and the centre of the galaxy.

Spatially the young blue populations fall on the bright arms of the Hα loop and filament while the older, redder populations are more evenly dispersed around the galaxy. This and the extremely young ages imply that the formation mechanism both is separate to the event that formed the star clusters in the centre of the galaxy and is intimately linked to the formation of the Hα filaments.

The star formation in the Blue Loop and Southern filament is ‘clumpy’, and there is evidence suggesting that there is a gradient in colours along these ‘clumps’. This and the observation of a broad range in colours in the blue population suggest that the event responsible for the star cluster formation is unlikely to have occurred rapidly. However, the range in ages of the population is very dependent on the models used and can only be precisely determined with spectroscopy.

We suggest formation mechanisms based on the disruption of the magnetic field supporting the filaments either as a shock from a buoyant radio bubble or by the filaments, fragmenting and falling back into the galaxy after being dragged out below such a bubble. If such a scenario is responsible for the star formation, then these outer stellar regions provide another link in the evolutionary cycle feeding the SMBH and regulating the cluster growth. Spectroscopic observations of these regions are needed to confirm that the stellar clusters are really in the LVS and to better determine their ages and kinematics.

The star formation rate in the Blue Loop is $\sim 20 \, M_\odot \, yr^{-1}$. The lifetime of the whole low-velocity filamentary system is therefore much greater than $10^{8}$ years.

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REFERENCES

Ashman K. M., Zepf S. E., 1992, ApJ, 384, 50
Boroson T. A., 1990, ApJ, 360, 465
Breggs S. A., Smiiders M. A. J., Boksenberg A., 1982, Nat, 300, 336
Brodie J. P., Strader J., 2006, ARA&A, 44, 193
Brodie J. P., Schroder L. L., Huchra J. P., Phillips A. C., Kissler-Patig M., Forbes D. A., 1998, AJ, 116, 691
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000 (BC03)
Cardelli J. A., Clayton G. C., Mathis J. S., 1989, ApJ, 345, 245
Carlson M. N. et al., 1998, AJ, 115, 1778
Cautalet A., Woodgate B. E., Brown L. W., Gull T. R., Hintzen P., Lowenthal J. D., Oliversen R. J., Ziegler M. M., 1992, ApJ, 388, 301
Conseilce C. J., Gallagher J. S. III, Wyse R. F. G., Lowenthal J. D., Oliversen R. J., Ziegler M. M., 1992, ApJ, 388, 301
Crawford C. S., 2004, in Mulchaey J. S., Dressler A., Oemler A., eds, Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution. Cambridge Univ. Press, Cambridge
Dixon W. V. D., Davidsen A. F., Ferguson H. C., 1996, AJ, 111, 130
Donahue M., Mack J., Voit G. M., Sparks W., Elston R., Maloney P. R., 2000, ApJ, 545, 670
Dunn R. J. H., Fabian A. C., Sanders J. S., 2006, MNRAS, 366, 758
Ekers R. D., van der Hulst J. M., Miley G. K., 1976, Nat, 262, 369
Fabian A. C., Nulsen P. E. J., 1977, MNRAS, 180, 479
Fabian A. C. et al., 2000, MNRAS, 318, L65
