ABSTRACT

We present simulated $J$- and $K$-band observations of stars in the Virgo and Coma clusters of galaxies using the proposed Next Generation Space Telescope with a Near-Infrared Camera, and discuss some of the scientific results that might be obtained. The proposed telescope will be able to resolve the brightest $\sim 3$ magnitudes of the red giant branches in the halos of galaxies in the Virgo Cluster and may be able to resolve stars at the tip of the red giant branch in the Coma Cluster. The simulations show that the background light is more important than the size of the telescope’s aperture in determining the limiting magnitude of the observations. Therefore we recommend that the Next Generation Space Telescope be placed in a $1 \times 3$ a.u. orbit to minimize background light.

Key words: space astronomy; NGST; stellar populations.

1. INTRODUCTION

Before the launch of the Hubble Space Telescope (HST) stellar populations could only be studied in detail in the Galaxy, the Magellanic Clouds, and the globular star clusters (GCs) of these galaxies. The main limitation was not the light-gathering capabilities of ground-based telescopes, but the crowding due to the small angular sizes of most external galaxies and the effects of atmospheric seeing. The superb resolution of the HST significantly reduced the apparent crowding of the stellar images allowing detailed stellar population studies to be made of many of the Local Group (LG) galaxies and GCs. The HST has also been able to resolve the brightest 1 to 2 magnitudes of stars in other nearby galaxies such as Centaurus A and galaxies in the Leo Group. The major limitation of the HST for stellar population studies is the diameter of the primary mirror (2.4 metres). The larger mirror on the proposed Next Generation Space Telescope (NGST), coupled with an expected resolution of $\sim 0''05$ to $0''1$, will make it possible to resolve individual stars at much greater distances than the HST can. The improved resolution and light-gathering ability, as well as the reduced background 3 a.u. from the Sun, will allow the study of stellar populations in galaxies in the Virgo Cluster and beyond.

All other factors being equal, a 4-metre NGST will receive $\sim 2.8$ times as much light per unit time as the HST does while an 8-metre NGST will receive $\sim 11$ times as much light per unit time. This corresponds to an increase in the limiting magnitude of 1.12 and 2.60 respectively, which will allow the study of stellar populations in the Virgo Cluster with a level of detail that is currently only possible in LG spiral and dwarf galaxies. The Virgo cluster, however, contains several elliptical galaxies and a cD galaxy. Therefore, the NGST will allow the study of stars in galaxies with a wide variety of morphological types and in a wide variety of environments. Being able to study the fossil record of star formation in these galaxies will provide valuable clues to the way in which these galaxies formed and evolved. Detailed studies of M31 (e.g. Holland et al. 1997, Rich & Mighell 1995) and M33 (e.g. Mighell & Rich 1995) with the HST have revealed dramatically different stellar populations from what are found in the Milky Way Galaxy, which suggests that the three major LG galaxies have had radically different formation and enrichment histories despite the three galaxies having similar morphological types and being located in the same environment. These effects must be well understood to support NGST studies of galaxies at cosmological distances.

2. SIMULATED OBSERVATIONS

We simulated NGST observations of fields in the Virgo and Coma clusters of galaxies using three telescope apertures (4-, 6-, and 8-metre) and two orbits (1 a.u. and 1 $\times$ 3 a.u.). We used the properties of the proposed NGST and Near-Infrared Camera (NIRCAM) as described in Stockman (1997). Table I lists the properties we assumed for the NIRCAM.

For a NGST located 1 a.u. from the Sun we assumed a background count rate equal to that of the HST’s NIC2 camera and scaled it to the NIRCAM’s pixel size. At 3 a.u. from the Sun we scaled the background count rates as indicated by Figure 2.2 of Stockman [1997]. Our adopted $J$- and $K$-band background...

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STELLAR POPULATIONS BEYOND THE LOCAL GROUP WITH THE NGST
it is difficult to make detailed simulations of observations with a space telescope that has not been built and whose orbit has not been determined. The following simulations are intended to show the relative capabilities of several different NGST apertures and orbits, and to compare the capabilities of the NGST with those of the HST. The simulations ignore cosmic rays (which are expected to affect more than 5% of the pixels for exposure times of $\lesssim 1000$ seconds (Stockman 1997)), so we set our exposures to 1000 seconds and ignored cosmic rays. We simulated 36 $\times$ 1000 second exposures in each of the $J$- and $K$-bands. This corresponds to one day of observing time if we assume 2.5 minutes of overhead time per exposure, or 28 HST orbits. Combined $J$- and $K$-band images were created for each field by taking the mean of all the exposures in each filter. The resulting combined images were reduced using the DAOPHOT II digital photometry software package (Stetson 1987). Aperture corrections were computed based on the input and recovered magnitudes of the brightest star in each field.

Table 1. NIRCAM.

| Property       | Value |
|----------------|-------|
| Dark Current   | 0.02  |
| Full Well      | 60,000|
| Gain           | 6     |
| Read-Out Noise | 15    |
| PSF FWHM       | 0.08  |

Table 2. The $J$- and $K$-band background count rates in $e^- \cdot s^{-1} \cdot pix^{-1}$ per pixel.

| Distance | $B_J$ | $B_K$ |
|----------|-------|-------|
| 1 a.u.   | 0.015 | 2.044 |
| 3 a.u.   | 0.002 | 0.204 |

count rates are listed in Table 2. For long exposures the background is dominated by zodiacal light and instrument glow (Stockman 1997). When the NGST is 3 a.u. from the Sun the amount of zodiacal light is reduced by a factor of $\sim 30$ to 100. As shown in Section 2.1 the reduction in the infrared background obtained by moving the NGST to 3 a.u. from the Sun corresponds to a significant improvement in the NGST’s ability to resolve and photometer individual stars in the Virgo Cluster. The actual background count rates in Table 2 include a contribution from instrument glow so the total reduction in the infrared background when moving from 1 a.u. to 3 a.u. is approximately a factor of 10.

We constructed $J$- and $K$-band images of an artificial star field at a projected distance of 172 $''$ ($\sim 13.3$ kpc) from the core of M87. This is twice the effective radius of the galaxy so the unresolved background light from M87 is small compared to the contribution from the sky and telescope glow. We added 115,000 artificial stars based on the colour–magnitude diagram (CMD) and luminosity function (LF) of the upper red giant branch (RGB) of M13. Background light, Poisson noise, and read-out noise were added to each image. Contamination from cosmic rays is not expected to affect more than $\sim 5\%$ of the pixels for exposure times of $\lesssim 1000$ seconds (Stockman 1997) so we set our exposures to 1000 seconds and ignored cosmic rays. We simulated 36 $\times$ 1000 second exposures in each of the $J$- and $K$-bands. This corresponds to one day of observing time if we assume 2.5 minutes of overhead time per exposure, or 28 HST orbits. Combined $J$- and $K$-band images were created for each field by taking the mean of all the exposures in each filter. The resulting combined images were reduced using the DAOPHOT II digital photometry software package (Stetson 1987). Aperture corrections were computed based on the input and recovered magnitudes of the brightest star in each field.

Table 3 lists the estimated limiting magnitudes of each of the simulated M87 observations. None of the 19 recovered stars in the simulated HST observations had S/N $\geq 5$.

Figure 1 shows the CMDs for the simulated HST and NGST observations of the halo of M87. All stars that were recovered in both the $J$- and $K$-band images are plotted. Figure 2 shows the $K$-band LFs for each simulation. The observed LF only agrees with the input LF down to some limiting magnitude, which depends on the telescope’s aperture and distance from the Sun. Fainter than this limiting magnitude the recovered LF rises more rapidly than the input LF does, which suggests that many of these detections are not real stars. Figure 3 suggests that detections with $\sigma \leq 0.2$ (corresponding to $\sigma_{J-K} \leq 0.3$) are probably real stars. Therefore we have taken the limiting magnitude of the simulated observations to be the magnitude at which $\sigma = 0.2$. This corresponds to a signal-to-noise ratio (S/N) of 5.

These results suggest that a telescope aperture of at least 6 metres will be needed to do stellar population studies in galaxies in the Virgo cluster if the NGST is placed in a 1 a.u. orbit. The reduction in the background obtained by using a 1 $\times$ 3 a.u. orbit results in the NIRCAM’s limiting magnitude becoming $\sim 1$ magnitude fainter. This would enable similar stellar population studies to be undertaken with a 4-metre NGST but the best results were obtained from a 6- or 8-metre NGST in a 1 $\times$ 3 a.u. orbit. In this scenario it should be possible to resolve the brightest two or three magnitudes of the RGB in M87 and other Virgo Cluster galaxies with $\sim 1$ day of observing time.

Horizontal branch (HB) stars in M87 should be lo-
This figure shows all of the recovered stars that appear in both the J- and K-band images for our simulated M87 data. The dots are the recovered stars while the large solid circles show the fiducial sequence for the input RGB. The left-hand label indicates the size and orbit of the telescope while the right-hand label indicates the number of exposures per filter.

Figure 2. This figure shows the input and recovered K-band LFs for the M87 simulations. The filled circles show the input LF, the dashed line shows the LF for all of the detections, and the solid line shows the LF for those detections with $\sigma_K \leq 0.2$ (i.e. S/N $\geq 5$).

Table 3. Estimated limiting magnitudes (where S/N $\geq 5$) for each of the M87 simulations.

| Telescope | $J_{\text{lim}}$ | $K_{\text{lim}}$ |
|-----------|-------------------|-------------------|
| HST       | ...              | ...              |
| 4m 1 au   | 26.3             | 25.3             |
| 6m 1 au   | 27.0             | 26.0             |
| 8m 1 au   | 27.6             | 26.6             |
| 4m 1x3 au | 27.0             | 26.0             |
| 6m 1x3 au | 27.9             | 26.9             |
| 8m 1x3 au | 28.6             | 27.6             |

simulation shown since they were not recovered with 36 × 1000 second exposures. Our simulations suggest that HB stars may be observable with $\sim 30$ hours of observing in each of the J- and K-bands with an 8-meter NGST in a 1 × 3 a.u. orbit.

2.2. The Coma Cluster

Recent HST WFPC2 observations of the tip of the RGB in Virgo Cluster galaxies (Harris et al. 1998) suggest that it may be possible to observe the tip of the RGB in the Coma Cluster using the NGST under optimum conditions. We simulated these observations in the manner described in Section 2.1. We constructed an artificial star field in the halo of NGC 4881 at a projected distance of 34" ($\sim 67$ kpc, or $\sim 2$ effective radii) from the core of NGC 4881, and reduced the images in exactly the same manner as was done for the simulated M87 observations. The resulting CMDs are shown in Figure 4. All stars that were cated at $K \sim 28.5$. These were not included in the...
recovered in both the $J$- and $K$-bands are plotted. The input and recovered LFs are shown in Figure 5.

Figure 4. This figure shows all of the recovered stars that appear in both the $J$- and $K$-band images for our simulated NGC 4881 data. None of these stars have S/N greater than \( \sim 2.5 \).

Figure 5. This figure shows the input LF (filled circles) and recovered LF (dashed line) for the NGC 4881 simulations. For all configurations of the NGST only the stars at the tip of the RGB are recovered and these stars have S/N < 5.

Table 4. The mean S/N of the stars at the tip of the RGB in the simulated observations of NGC 4881.

| Telescope | $S/N_J$ | $S/N_K$ |
|-----------|---------|---------|
| HST       | 2.1     | 1.8     |
| 4m 1 au   | 2.2     | 2.3     |
| 6m 1 au   | 1.6     | 1.7     |
| 8m 1 au   | 2.3     | 2.2     |
| 4m 1\times3 au | 2.1     | 2.1     |
| 6m 1\times3 au | 2.5     | 2.3     |
| 8m 1\times3 au | 2.2     | 2.2     |

Two of the primary goals of the NGST are (1) to study the formation of galaxies and (2) to study the structure and dynamics of galaxies at redshifts of $z \sim 2$. Galaxies at large redshifts can only be studied through integrated colours and spectra. The detailed physical properties of these galaxies are then deduced through these integrated properties. In order to understand the relationship between the integrated properties of high-redshift galaxies and their stellar populations it is necessary to understand how the stellar content of a galaxy affects the observed integrated light and spectra.

Some of the results of studying stellar populations in a large number of galaxies of different Hubble types and in different environments are discussed below.

3. SOME SCIENTIFIC OBJECTIVES

3.1. Age

If a Virgo Cluster galaxy is currently undergoing star formation the upper main sequence will be resolved with the NGST. If the main-sequence turn-off can be located, the age of the stars can then be determined with a high degree of precision. An intermediate-aged population can be identified by the presence of super-luminous asymptotic giant branch (AGB) stars. Photometric scatter in the RGB will make distinguishing between RGB and AGB stars difficult for some of the proposed NGST designs. However, if the NGST is placed in a $1 \times 3$ a.u. orbit and has a 6- or 8-metre aperture detailed studies will be possible. Studies of halo and bulge fields in M31 (Holland et al. 1996, Rich & Mighell 1995) as well as fields in M33 (Mighell & Rich 1995) show that it is possible to use the lack of super-luminous AGB stars to constrain the age distribution. The uncertainties in the photometry obtained in those studies were similar to the photometric scatter in our simulated NGST observations of the RGB of M87. The record of star
formation contained in the brightest few magnitudes of a CMD can be combined with dynamical information on other Virgo Cluster galaxies to study the relationship between close encounters between galaxies and star formation in a large number of galaxies of different morphological types.

3.2. Metallicity

There is a relationship between the shape of the upper RGB and metallicity (Da Costa & Armandroff [1990]). If a stellar population contains a range of metallicities, the RGB will be broader than would be expected from the photometric uncertainties alone. A grid of model RGBs with known metallicities can be placed over the observed RGB and used to interpolate a metallicity value for each star. The broadening of the derived metallicity distribution due to photometric scatter can be removed by deconvolving the observed error distribution from the metallicity distribution. This technique has been used to determine the metallicities of several GCs in LG galaxies (e.g. Holland et al. 1997) and to find the metallicity distribution of stars in the halo of M31 (e.g. Holland et al. 1990). Our results suggest that the metallicity distributions of stellar populations in the Virgo Cluster can be estimated from the curvatures and widths of their RGBs. The high resolution and large field of view of the NIRCAM (4′ × 4′) will make it possible to rapidly map the dependence of metallicity on position in the halo of a galaxy in the Virgo Cluster. This may allow the identification of recent mergers by locating areas of anomalous metallicity in a galaxy’s halo. It can also be used to trace star formation history as a function of position in a galaxy.

CMD techniques can be used to determine the metallicity of stellar populations that are too diffuse to permit spectral determinations of elemental abundances. Since CMD techniques work best in uncrowded fields they are a natural complement to NGST spectral observations of the bulges and cores of galaxies.

3.3. Distance

One of the Key Projects for the HST was to investigate the extragalactic distance scale using Cepheid variables in galaxies in the Virgo Cluster (e.g. Kenmivct et al. 1998). High-quality CMDs and colour–colour diagrams of the fields containing Virgo Cepheids will allow improved estimates of the reddening and metallicity corrections that need to be applied to Cepheid observations. Both the tip of the RGB and the curvature of the upper RGB can be used to determine the distance to a galaxy if the metallicity is known. An 8-metre NGST in a 1 × 3 a.u. orbit will be able to resolve HB stars with ~ 7 days the resulting observation will be comparable to the best existing HST observations of stars in the halo of M31.

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4. CONCLUSIONS

All of the proposed designs for the NGST will allow colour–magnitude studies of stars in the Virgo Cluster to be performed, although better results are obtained with larger apertures and greater distances from the Sun. Reducing the amount of background light is more important than increasing the telescope’s aperture for resolving stars in distant galaxies. This is because reducing the background results in a reduction in the amount of Poisson noise. This leads to an increase in the signal-to-noise ratio for faint stars which makes them easier to detect and photometer. The same is true for resolving stars in Coma Cluster galaxies.

Our results suggest that the NGST will be able to study resolved stellar populations in Virgo Cluster galaxies at similar levels of detail similar to studies of LG galaxies using large ground-based telescopes. If an 8-metre NGST in a 1 × 3 a.u. orbit observes a Virgo Cluster galaxy for only ~ 7 days the resulting observation will be comparable to the best existing HST observations of stars in the halo of M31.