100 Times Faster and 3 Times Sharper:
Background-Dominated Observations of Stellar Populations with an 8-meter Optical-UV Space Telescope

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Abstract. An 8 m successor to the Hubble Space Telescope (HST) would make incredible gains in the study of stellar populations, especially in the Local Group. If diffraction-limited at 0.5 \( \mu m \), the “Next HST” could produce high-resolution imaging of faint sources over a wide field in 1 percent of the time needed with the HST. With these capabilities, photometry of the ancient main sequence could be obtained for many sight-lines through Local Group galaxies, thus determining directly the ages of their structures and providing a formation history for the Local Group populations.

1. Introduction

One of the primary quests of observational astronomy is measuring the formation history of giant galaxies. Recently, renewed interest in formation via accretion of dwarf galaxies has been sparked by the discoveries of the Sagittarius dwarf galaxy falling into the Milky Way (Ibata et al. 1994) and of a tidal stream in the Andromeda halo (Ibata et al. 2001). With large investments of Hubble Space Telescope (HST) time, color-magnitude diagrams that reach the ancient main sequence can be constructed for selected fields in galaxies of the Local Group, thus providing accurate ages for their structures via the same techniques traditionally used to date the populations in Galactic globular clusters. Unfortunately, these studies are limited by the long integration times needed to reach the main sequence at the distance of Andromeda (the nearest spiral to our own), and by the stellar crowding that can be addressed at the HST resolution. However, an 8 m optical-UV space telescope, diffraction-limited at 0.5 \( \mu m \), would crack this field wide open, because of a simple concept that is often overlooked in discussions of an HST successor: The time to reach a given signal-to-noise for background-dominated photometry of point sources scales as aperture to the fourth power, for a telescope that is diffraction-limited at a given wavelength.

2. Background-Dominated Photometry

At a given wavelength, the width of a resolution element decreases linearly with the aperture diameter \( (D) \), and thus the area of a resolution element on the sky decreases as \( D^2 \). Because the collecting area increases as \( D^2 \), the sky counts in
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a resolution element remain constant as aperture increases. The signal-to-noise ratio \( (S/N) \) for background-dominated photometry thus scales as:

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\frac{S}{N} \propto \frac{S \times t \times \left( \frac{D}{d} \right)^2}{\sqrt{B \times t + S \times t \times \left( \frac{D}{d} \right)^2}} \propto \frac{S \times t \times \left( \frac{D}{d} \right)^2}{\sqrt{B \times t}} \propto S \times \sqrt{t} \times \left( \frac{D}{d} \right)^2
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where the source rate is \( S \), the sky background rate is \( B \) \( (B \gg S) \), the exposure time is \( t \), and the source distance is \( d \). Thus, with other parameters fixed, the distance at which you can see a source scales as \( D^{-2} \), the flux you can measure scales as \( D^{-4} \), and the exposure needed scales as \( D^{-4} \). Current HST observing programs studying faint stars would be 100 times faster with an 8 m optical-UV space telescope, without assuming any advances in optical coatings, detector efficiencies, etc. (see Figure 1). These dramatic gains will be even larger than those realized by the Next Generation Space Telescope (a 6 m telescope, diffraction limited at 1 – 2 \( \mu \)m, with higher background in its near-IR channels).

Figure 1. The exposure time needed to obtain photometry of the Sun at the distance of Andromeda, assuming a telescope that is diffraction-limited at 0.5 \( \mu \)m. The Sun makes a good fiducial because of its familiarity and its proximity to the MSTO in the color-magnitude diagram of an old stellar population.

Many difficult problems, requiring large investments of HST observing time (more than 100 orbits), become trivial with an 8 m version of the HST. The shorter integrations make it possible to study many more sight lines through Local Group galaxies, and the superior resolution allows investigation into structures that are much more crowded. Because the exposure time for a given \( S/N \) is so much faster, one can also study variability in regimes previously unreachable. Examples of programs that would benefit greatly from a larger optical-UV space telescope include age-dating Local Group populations using the main sequence turnoff (MSTO), studying the white dwarf cooling curve in Galactic globular clusters, and microlensing searches for dark matter.

3. Simulations

To dramatize the gains made in imaging of stellar populations, I have created two simulations of imaging in the bulge of Andromeda, of which only small subsections are shown in Figure 2. The first simulation shows a combination of three bands from a hypothetical HST imaging program using the Advance Camera for Surveys (ACS) and its Wide Field Camera (WFC), assuming the
native pixel size (50 mas). This false-color image combines F435W data (120 hrs) for the blue channel, F606W data (42 hrs) for the green channel, and F814W data (49 hrs) for the red channel. Although such deep exposures could detect isolated stars on the ancient main sequence at this distance, the crowding and surface brightness of the unresolved stars in the bulge and disk would preclude detection of the MSTO. The second simulation shows the same field as imaged with the same bandpasses using the “Next HST” (NHST; an 8 m version of the HST), assuming 1/10\textsuperscript{th} the exposure time; note that only 1/100\textsuperscript{th} of the HST time is needed to match the HST S/N. The NHST simulation resolves the ancient MSTO. The NHST would likely have two imaging cameras: a wide-field camera that undersamples the point spread function (PSF) with an approximately 1 square degree field, and a high-resolution camera that critically samples the PSF (7.5 mas pixels) with a field-of-view comparable to the current ACS/WFC on HST (204'' × 204''). The NHST simulation uses the high-resolution camera, which provides the same field, but with a PSF that is both critically sampled and 3.3 times narrower than the PSF in the HST simulation.

The simulations reproduce the surface brightness in a field about 8 arcmin from the center of Andromeda, where the bulge and disk populations have approximately the same surface brightness (Baggett, Baggett, & Anderson 1998). The full simulated images include a globular cluster, young open cluster, and tidal stream from a disrupted galaxy (10% overdensity). All of the components (disk, bulge, stream, and clusters) were constructed using the isochrones of Bertelli et al. (1994). Figure 2 shows 7.1'' × 5.4'' subsections in the vicinity of the Andromeda globular cluster.

4. Summary

For background-dominated photometry of stellar populations, an 8 m version of the HST would be 100 times faster than the current HST, and provide 3 times the resolution. Although the increased resolution would allow photometry in fields that are currently impossible with the HST, the reduction in exposure time is not an advance that should be treated lightly. Obviously, for a given field that can be resolved with the HST, one can always argue that requesting one hundred orbits of HST time would be easier than building an 8 m HST and observing for one orbit. However, a factor of 100 in exposure time allows one to resolve the main sequence in dozens of sight-lines throughout the Local Group, a program that is simply impossible with the HST, no matter what fraction of its remaining lifetime is devoted to the problem. Such a program would allow the direct age determination of structures (disks, bulges, halos) in Local Group galaxies, providing a formation history for these galaxies and their components.

References

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Figure 2. Simulated images in the bulge of Andromeda, near a globular cluster (see text for details). Top panel: HST/ACS/WFC; bottom panel: NHST.