Tracing the Histories of Galaxies from Beginning to End: the Stellar Populations of Nearby Galaxies

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Determining the times at which the different morphological types of galaxies appeared and the order in which they assembled their distinct components is key to understanding the processes connecting galaxy formation with the production and dispersal of the chemical elements that gave rise to planets and life. Only by examining the resolved stars in a sample of mature elliptical, spiral, and dwarf galaxies can we trace their star-forming and element-producing histories from beginning to end. These histories hide yet-to-be discovered principles that guide the evolution of galaxies; however, the great distances to even the nearest spiral and elliptical galaxies place most of them out of reach of current telescopes. For a new leap forward, we require the uniquely powerful capabilities of both JWST and GSMT.

We will use JWST, which excels at stable, deep near-infrared imaging, to measure photometric ages and abundances of stars in the low surface brightness halos of spiral and elliptical galaxies and in dwarfs. Such halos are thought to harbor some of the earliest stellar generations, yet also contain the residue of late-time accretion, a process whose importance is not yet fully understood. In the bulges and disks of spiral galaxies and in the main bodies of elliptical galaxies, where stellar densities are extreme, we will use the excellent adaptive optics-corrected images of GSMT to measure near-infrared photometry of faint stars, and JWST to produce a stable calibration from bright stars. The relationships between these high surface brightness components of galaxies and their low surface brightness halos are central to understanding the processes of galaxy assembly and the production and transfer of chemical elements. Finally, we will use the high-resolution spectroscopy unique to GSMT to measure the abundances of important diagnostic chemical elements in stars in every component of all kinds of galaxies, providing critical clues to help us unravel the complex problem of the origin of stellar populations.

1. The Perspective of the Milky Way Galaxy

Our picture of galaxy formation and evolution must account for the old ages, low metallicity, and hot dynamics of the Galactic halo and its globular clusters; the old age, intermediate metallicity, and slow rotation of the thick disk; the steady star formation rate, higher metallicity, and faster rotation of the thin disk; and the declining star formation rate, nearly solar metallicity, and hot dynamics of the bulge. However, before drawing global conclusions from these features of the Milky Way, we must recognize that important aspects of the Milky Way's content and structure may be peculiar to its history or may, like the accretion of the Sagittarius dwarf galaxy[1] and the current burst of star formation in the nucleus[2], be stochastic in nature. Studying a sample of galaxies of different morphologies and in a range of environments is thus critical to developing a realistic picture of galaxy formation and evolution.

2. Broadening our Perspective: the Dwarfs, M31, and Cen A

The Milky Way has shaped the modern view that galaxies form hierarchically through the merging of clumps of gas and stars, accompanied by slower accretion of gas. In this picture, dwarf galaxies may represent protogalactic fragments that have not yet been accreted into larger galaxies. However, a recent VLT spectroscopic study of red giants in four dwarf spheroidal companions to the Milky Way found very different chemical signatures in even the oldest dwarf spheroidal stars compared to stars in the Milky Way bulge, disk, and inner halo[3]. It thus appears that if the Milky Way formed hierarchically, it must have accreted most of its mass as gas at very early times, rather than through an extended period of dwarf galaxy cannibalization.

But is the Milky Way peculiar? Deep recent imaging of the low surface brightness halos of M31, the closest large spiral galaxy, and Cen A, the closest elliptical, show that there are strong differences between the Milky Way and other galaxies. HST WFPC2 photometry of the halo of Cen A reveals that it has a metallicity distribution function that is peaked at the metal-rich value of [m/H]~-0.4, with only a small fraction with metallicity <-1.0[4]. By contrast, its population of globular clusters contains numerous clusters with metallicities as low as those of the Milky Way. Ground-based studies have for some time shown that M31's halo is also dominated by a metal-rich component[5,6,7], indicating that it is more similar to Cen A, an elliptical galaxy, than the Milky Way. New observations with HST and ACS indicate that M31's halo is composed by more than half of intermediate-age (6-8 Gyr) stars, challenging the conventional wisdom that halos are exclusively old[8]. A natural explanation for the intermediate age and metallicity of both the M31 and Cen A halos is late merging with smaller galaxies, a process which appears to be ruled out in the Milky Way.

3. The Need for JWST and GSMT

We thus do not yet know how the components of different morphological types of galaxies formed, or even in what order they appeared. We also do not understand the chemical signatures of the first generations of stars, nor the evolution and dispersal of the elements with time. The combination of JWST and GSMT stand to make major advances in addressing our ignorance. In particular:

- We need JWST to image the low surface brightness halos of nearby galaxies such as M31 and Cen A to greater depths, allowing comparison of the star formation histories of several spiral galaxy halos with that of ellipticals. Figure 1 shows a simulation of an M31 halo field observed with both JWST and GSMT, demonstrating their similar predicted performance. While the GSMT's larger mirror compensates for the higher sky background compared to JWST in this simulation, the stability of the JWST PSF will make it considerably more useful for near-IR, sensitivity-limited broadband exposures.

- In high-surface brightness spiral bulges and in the main bodies of elliptical galaxies, observations are limited by *crowding* long before the sensitivity limit is reached. For observations in such regions, which are critical for deciphering the formation histories of galaxies, JWST will perform no better than today's AO-corrected 8-10m telescopes, which have similar diffraction-limited resolutions. By contrast, the GSMT's ×4 better resolution will allow it to reach much greater photometric depths in crowded regions (Figure 2). The lower Strehl of GSMT's AO-corrected PSF is of no consequence to the photometric depth, as its effect is simply to increase the effective sky background and thus increase the exposure time needed to reach the crowding limit. However, variations in the Strehl ratio across the image will increase the photometric scatter if left uncorrected; the time variability of the Strehl ratio will also make the absolute photometric calibration uncertain. It will thus be critical to calibrate the GSMT observations of high surface brightness regions of galaxies with JWST photometry of the brighter, less crowded stars.
- Current telescopes are limited to measuring elemental abundances through spectroscopy in only the Milky Way and its dwarf companions. High-resolution spectroscopy with GSMT will extend this very exciting work to include red giants in M31 and its dwarf companions, thus vastly increasing the volume within which we have detailed abundance information. Indeed, it is likely that this volume will represent a "closed box" within which we may consider the problem of galaxy formation and evolution to be self-contained.

Table 1 summarizes the comparison of the capabilities of JWST and GSMT for stellar populations studies.

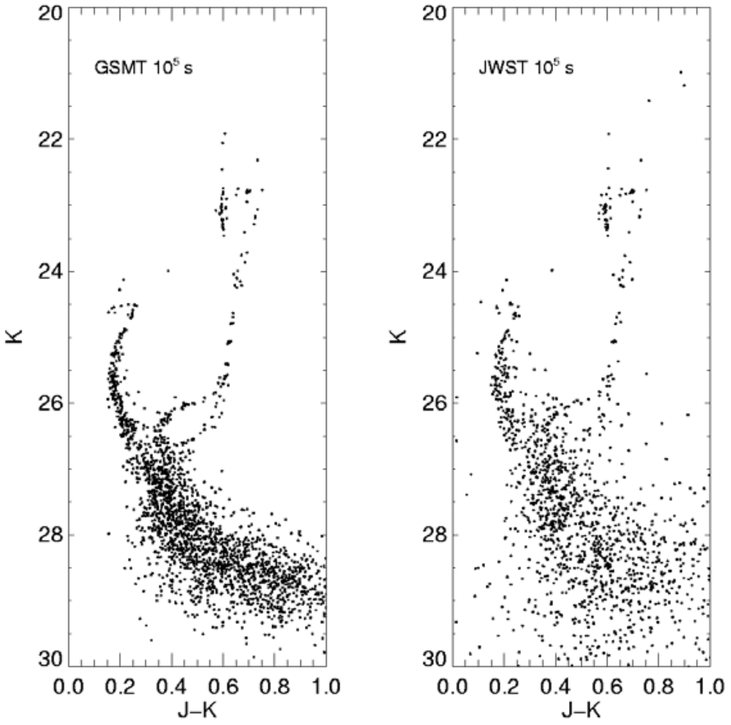

Figure 1 Simulating the halo of M31. These color-magnitude diagrams were recovered from simulated GSMT and JWST images totaling 10^5 seconds of exposure and containing an equal mix of 1 Gyr, 5 Gyr, and 13 Gyr-old stars and having surface brightness K=22 mags arcsec^{-2}. While the cleaner PSF of the GSMT produces somewhat better photometry, the photometric depths are approximately equal in this relatively uncrowded field.

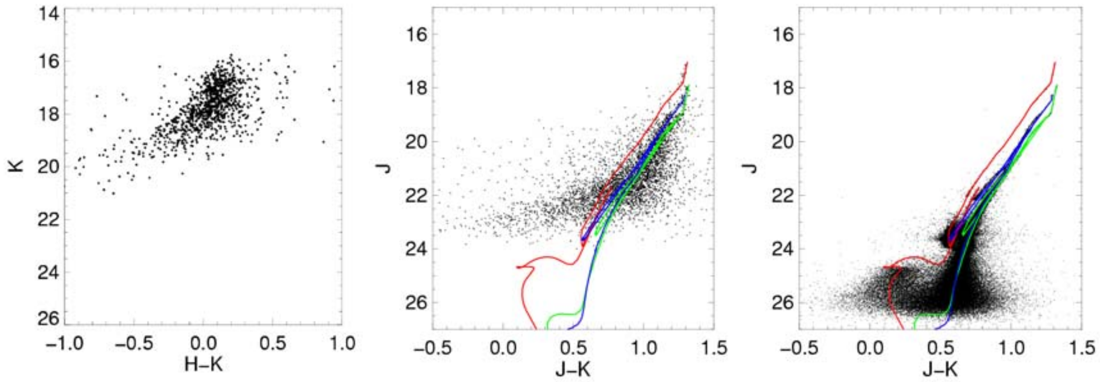

Figure 2 Stellar populations at the center of M32. Left: Color-magnitude diagram of the central 30” of M32, as observed with Gemini N+Hokupa’a (Davidge et al. 2000). Middle: JWST color-magnitude diagram from a simulation having a stellar population mix and surface brightness similar to that at the center of M32. The depth is K~21, only somewhat deeper than K~19 for Hokupa’a. Right: GSMT simulated color-magnitude diagram of the center of M32, which achieves a depth of K~26. The superior angular resolution of GSMT enables much higher precision photometry in this crowded region.

	GSMT	**JWST**	**Key application**
Spatial resolution	0.”008 at J 0.”015 at K	~0.”032 ≤1 μ 0.”07 at K	All (crowded fields)
PSF stability	20%-40% spatial variability (stable?), ~50% temporal variability?	Stable to <2%	All (point-source photometry)
Imaging depths	J=30.0, K=28.2 in 10^5 s (S/N=10) J=28.8, K=27.0 in 10^4 s	J=29.8, K=28.5 in 10^5 sec (S/N=10)	Deep halo CMDs
Spectroscopic depths	H=25 (R=3000, S/N=10) in 5x2000 s R=21.5 (R=25000, S/N=10) in 5x2000 s	H=22.5 (R=2000, S/N=10) in 10^5 s R=21.5 (R=2000, S/N=10) in 10^5 s	Red giant element abundances, stars in massive clusters, brown dwarf masses and temperatures
Observing efficiency	<25%? (issues: weather, seeing distribution, MCAO efficiency, etc.) Unlimited lifetime?	77% estimated (but has a 5 year lifetime)	Long exposures, survey mode
FOV	~1’	2.’2	Low surface brightness regions, survey mode

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