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A Systematic Study of the Stellar Populations and ISM in Galaxies out to the Virgo Cluster:

near-field cosmology within a representative slice of the local universe

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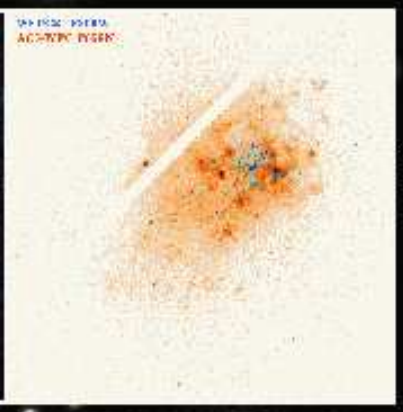
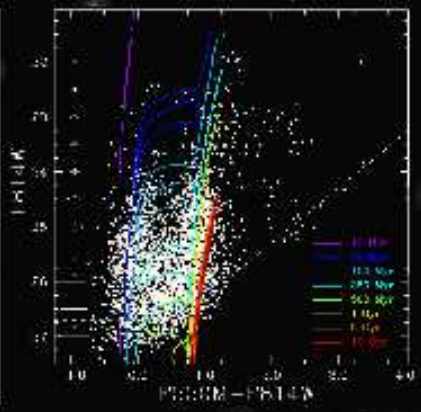
Science White Paper for the Astro2010 Decadal Survey
Panel(s): The Galactic Neighborhood (GAN) & Galaxies across Cosmic Time (GCT)





Abstract: We present a compelling case for a *systematic* and *comprehensive* study of the resolved and unresolved stellar populations, ISM, and immediate environments of galaxies throughout the local volume, defined here as $D < 20$ Mpc. This volume is our cosmic backyard and the smallest volume that encompasses environments as different as the Virgo, Ursa Major, Fornax and (perhaps) Eridanus clusters of galaxies, a large number and variety of galaxy groups (e.g., Sculptor, M 81, M 83, CVn I and II clouds, M 51, M 101, M 74, NGC 5866, M 104, and M 77 groups), and several cosmic void regions. In each galaxy, through a pan-chromatic ($\sim$160–1100 nm) set of broad-band and diagnostic narrow-band filters, ISM structures and individual luminous stars to $\gtrsim$1 mag below the TRGB should be resolved on scales of <5 pc (at $D\lesssim 20$ Mpc, $\lambda\sim 800$ nm, for $\mu_I \gtrsim 24$ mag arcsec^{-2} and $m_I^{\rm TRBG} \lesssim 27.5$ mag). Resolved and unresolved stellar populations would be analyzed through color-magnitude and color-color diagram fitting and population synthesis modeling of multi-band colors and would yield physical properties such as spatially resolved star formation histories. The ISM within and around each galaxy would be analyzed using key narrow-band filters that distinguish photospheric from shock heating and provide information on the metallicity of the gas. Such a study would finally allow unraveling the global and spatially resolved star formation histories of galaxies, their assembly, satellite systems, and the dependences thereof on local and global environment within a truly representative cosmic volume. The proposed study is not feasible with current instrumentation but argues for a wide-field ($\gtrsim$250 arcmin^2), high-resolution ($\lesssim 0\farcs02$–$0\farcs065$ [300–1000 nm]), ultraviolet–near-infrared imaging facility on a 4 m-class space-based observatory.

Keywords: galaxies: nearby — galaxies: stellar populations — galaxies: ISM — galaxies: satellites — galaxies: origins/assembly — ISM: star formation — ISM: feedback — near-field cosmology — stellar archeology — star formation

At the present epoch, most of the baryonic matter that condensed into galaxies is locked into stars. The stellar populations of galaxies not only record the history of baryonic matter, e.g., through chemical abundances and stellar spatial distributions, but also its rate of evolution via the star formation process. The visible forms of galaxies are shaped by a series of complex processes which convert dissipative interstellar matter into nearly collisionless stars. Despite the success of current theoretical models in following the growth of dark matter structures, significant problems remain in understanding how the baryonic components of galaxies develop. These include, for example, the low numbers of visible dwarfs and satellite galaxies relative to the predicted swarms of low mass dark matter halos around giant systems and the comparatively high angular momenta and old ages of galactic disks. Whether these difficulties represent fundamental issues with the hierarchical dark matter model, a lack of understanding of star formation processes and their feedback on galactic scales, or a lack of representative data spanning the full range in cosmic environment is yet unclear.

To advance our understanding of the star formation and chemical enrichment histories of the stellar systems within the $D < 20$ Mpc local volume, one would need access to the vacuum UV through near-IR wavelength regime. The UV is uniquely sensitive to hot sources such as massive young stars, low-mass accreting protostars, and certain types of old, highly evolved stars. Deep UV observations shortward of 365 nm of A and F-type stars, for example, are particularly important for tracking metal enrichment, star formation histories, and galaxy disk evolution. In older ($>$5 Gyr)

stellar populations, helium-burning stars in advanced evolutionary phases have surface temperatures >10,000 K, making them UV-bright. These hot objects are not only important in their own right, but also provide key information on mass loss during the red giant branch (RGB) evolution which precedes the hot phases. Stellar mass loss is a central problem in stellar astrophysics and is related to a number of other important processes, such as dust production, X-ray emission, and accretion flows. Many key diagnostics of interstellar gas and dust (ISM) are found also only at wavelengths shortward of 400 nm, including the 217.5 nm peak in the dust extinction law, and a number of important plasma emission lines (e.g., [O II]$\lambda\lambda$372.7nm, Mg II λ279.9nm and Lyα). The 150–250 nm region is also one of the *darkest* parts of the natural sky background above the Earth's atmosphere, permitting the detection of extremely faint sources. *Wide-field, high-resolution vacuum-UV imaging would open up a new window on this last under-explored corner of normal stellar evolution*.

Stellar populations contain the histories of evolution of the baryonic components of galaxies. Accessing this information is complicated by the presence of multiple stellar population components projected along each sightline, effects of interstellar dust on observed spectral energy distributions, and the relatively low brightnesses of outer regions of galaxies relative to the sky. Multi-band UV through near-IR ($\sim$200–1100 nm) measurements from space are required to derive extinction corrected stellar SEDs with sufficient precision to distinguish differences in metallicity and age. Unraveling the star formation histories of nearby galaxies (and spatial variations therein) *in detail* requires one to resolve individual stars to $\gtrsim$1 mag below the Tip of the RGB (TRGB). Although *HST* would in theory be capable of accessing the TRGB out to $\sim$12 Mpc, in practice *very* few studies have been able to push beyond 7 Mpc because of *HST*'s limited aperture (exposure times comparable to those in the Deep and Ultradeep Fields would be required). A particularly novel opportunity enabled by a larger aperture and similar or higher resolution would be to resolve red K-giant stars within star streams known to exist within the Virgo Cluster in the form of structure in the diffuse intra-cluster light. This would allow unraveling for the first time the 3D structure, kinematics and galaxy assembly history within the Virgo Cluster. *Space-based wide-field high-resolution optical–near-IR imaging would open up a new window of discovery space that remains inaccessible to or exceedingly inefficient with next-generation giant ground-based telescopes*.

Previous space-based UV–near-IR imaging facilities, however, emphasized either low spatial resolution and wide fields (e.g., *GALEX*; strictly UV, minimal filter set [n=2]) or high resolution and small fields (e.g., *HST*). For a study of both the resolved stellar populations *and* its dependence on the global structure and evolution of nearby galaxies, one would need to combine:

- ***(1)*** a large field of view (FoV) that is well-matched to the angular sizes of nearby galaxies and their satellite systems;
- ***(2)*** sensitivity to detect at $\gtrsim 5\sigma$ individual RGB stars to $\gtrsim$1 mag below the Tip of the RGB (TRGB; $M_I^{\rm TRBG}\simeq-4.0$ mag, $m_I^{\rm TRBG}\lesssim$27.5 mag);
- ***(3)*** high angular resolution that allows resolving individual luminous RGB stars at linear scales of <5 pc out to $\sim$20 Mpc (at $\lambda\sim$800 nm and $\mu_I\gtrsim 24$ mag arcsec^{-2}); and
- ***(4)*** a sufficiently rich complement of UV–near-IR broad-, medium- and narrow-band filters to provide physically meaningful diagnostics on both stars and ISM.

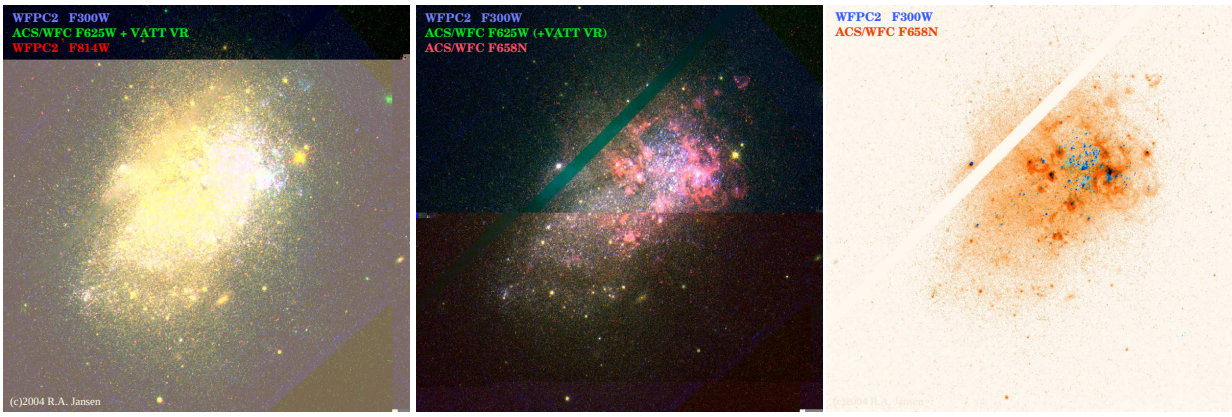


Fig. 1 — Three views of NGC 3738, a nearby Irregular galaxy, whose star formation history is characterized by episodes of vigorous star formation. (*a*) broad-band filters highlight the spatial distribution of stellar populations of various ages, (*b*) broad- and narrow-band images highlight the interplay between star formation and the ISM, the deposition of mechanical energy, (*c*) a mid-UV–Hα composite highlights the relation between the hot young stars that dominate the mid-UV and the ionized ISM. Various stages of the star-formation cycle, from deeply embedded and obscured star formation to cluster formation and break-out, can be identified. Whereas *HST* observations like these tend to be shallow and rarely provide simultaneous full coverage and <5 pc resolution, we here advocate a systematic study of the star formation histories and current massive star formation and its feedback within galaxies and their surrounding satellite galaxy systems, in cosmic environments as different as rich clusters, galaxy groups and void regions.

Color-magnitude and color-color diagrams obtained by *HST* and large ground-based telescopes of the resolved stellar populations within nearby galaxies enabled enormous leaps forward in our understanding of the stellar mass distributions and star-formation histories within our own and nearby ($D \lesssim 6$ Mpc) galaxies. Pushing that capability out to 20 Mpc, with large fields of view sampled with sufficient sensitivity and sampled at linear scales <5 pc would provide access to galaxies within a large and varied number of galaxy groups as well as the nearest clusters (Ursa Major and Virgo).

For higher-surface brightness regions and for serendipitously observed more distant galaxies, where individual stars cannot be resolved, the constituent stellar populations can still be deduced from their integrated light, since the integrated UV energy distributions of stellar populations evolve strongly over timescales up to 3 Gyr. The high-sensitivity region is shortward of ~400 nm, where the confluence of hydrogen

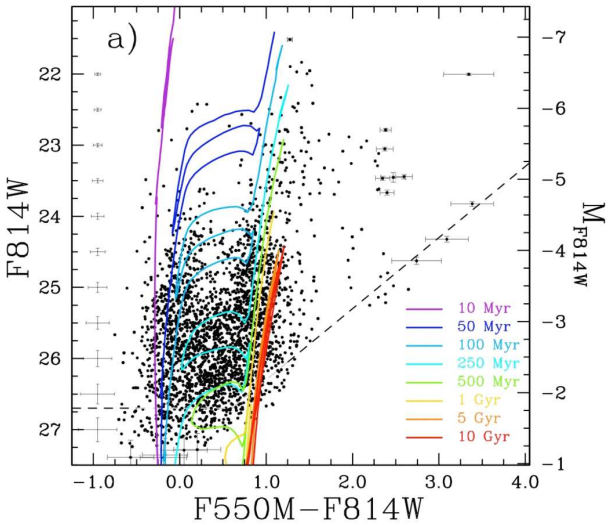


Fig. 2 — *HST*/ACS-HRC I vs. $(V-I)$ color-magnitude diagram of the resolved stellar populations within nearby metal-poor dwarf irregular galaxy CGCG 269-049 (Corbin et al. 2008). Padua isochrones are overlayed, demonstrating a complex star formation history with stellar populations of ages ranging from <100 Myr to ≳10 Gyr. At 5 Mpc, the TRGB is discernable at $I = 24.5$ mag. We advocate a UV–near-IR facility that would deliver CMDs of similar quality out to the Virgo Cluster.

absorption lines in hotter stars and the Balmer Jump and metallic absorption features in cooler ones begin to strongly affect the gross spectral structure. The UV will provide the parameters needed to measure star formation rates and break age–metallicity degeneracies in disecting composite stellar populations, and recover star-formation histories.

The UV allows direct detection of the massive stars responsible for most of the ionization, photodissociation, kinetic-energy input, and element synthesis in galaxies. These processes are responsible for much of the astrophysics of the universe. By contrast, most other methods of studying massive star populations yield only indirect measures since they rely on re-processing of the UV photons by the surrounding medium (H II regions or dust clouds). Furthermore, since the production of Lyman-continuum photons by young populations rapidly declines after $\sim$5 Myr, these other methods probe star formation only over a short period, which constitutes a tiny fraction (0.05%) of the lifetime of a galaxy. By comparison, the short-wavelength continuum below 400 nm remains a sensitive indicator of star-formation histories for ages up to 100$\times$ greater.

Key scientific themes that have arisen from recent advances

Near Field Cosmology: the oldest stellar populations. It is useful to ask *where* the oldest stars are located. We know that in the Milky Way they reside in the spheroidal halo, in the LMC and SMC they have the largest radial scale of any stellar population, and they usually are the least centrally concentrated stellar component of dwarf spheroidals. However, even in nearby galaxies these results only apply in a mean sense. With the growing realization of the importance of interactions in the lives of galaxies, as demonstrated by the discovery of tidal debris streams and plumes in, e.g., the Milky Way, M 31, M 81, and NGC 4013, the old star distribution merits reexamination. Are older stars asymmetrically distributed in the outer regions of galaxies, as expected if they were contributed by dissolving satellites? Data for inclined galaxies also will provide information on globular cluster systems, bulge vs. disk stellar populations, disk vertical structures, dust lane forms, warps, and a variety of other features on intermediate galactic scales. Each of these connects in useful ways to the evolutionary history and thus provides an empirical base for application of the expertise of the astronomical community.

Star Formation and its Products. The existing combination of ground-based and *HST* imaging provides an excellent base from which to design investigations of the nature and extent of star forming sites. Investigations of connections between drivers, if any, for star formation — spiral arms, interactions, etc., as well as basic galactic properties — are essential for understanding how feedback operates. A survey of the local $D < 20$ Mpc volume provides the range of galaxy types, luminosities, cosmic environment, and the sensitivity and statistics to support a complete study of the association of compact clusters and regions of star formation. From programs like *SINGS* and other recent and ongoing ground-based surveys, global star formation rates and time scales are anticipated to be known. We then can compare the small scale characteristics of star formation, an intrinsically local process, with the overall galactic environment. Are these statistically connected and, if so, how? By combining deep mid-UV and narrow-band Hα observations, it becomes possible to also address the escape fraction of ionizing radiation in a variety of galaxies. This question is particularly important in low metallicity dwarf galaxies which may have traits in common with the types of objects responsible for finishing reionization of the universe at redshifts $z > 6$.

Are Galactic Disks Growing? As already demonstrated by *GALEX*, young stars have high contrast against the sky in the mid-UV. This spectral range therefore opens the way for mapping star

formation in low-density environments, including the outer disks of galaxies. A next-generation wide-field UV–near-IR space observatory must offer major advantages in sensitivity and resolution over the pioneering results from *GALEX*. Hence, we would be able to determine ages and photometric stellar masses for small star forming complexes of the type that appear to populate the outer disks of galaxies, ranging from small irregulars to giant spirals. From these, star formation rates per unit area and, thus, disk growth rates can be estimated.

Galactic Centers. Centers of galaxies are dumping grounds. Baryonic material that ends up in the central zone of a galaxy has experienced substantial dissipation and loss of angular momentum. Yet it is not uncommon to find high-density stellar and gas systems coexisting within 1 kpc of the centers of galaxies. Centered in this zone are the nuclei themselves, many of which harbor massive black holes. We would be able to systematically chart the stellar properties of nuclear environments. Where and in what ways are stars formed (clusters, scaled OB associations, spiral arms, rings, clumps)? How does star formation relate to the properties of nuclei on small scales and on the other side to the surrounding main disk? How are bars, both large and nuclear, related to the structure and activity levels in nuclei?

A Survey of Nearby Galaxies. We propose to learn how galaxies work, through studies of their stars, ISM, and immediate environments, and to build the definitive UV–near-IR photometric imaging database of galaxies within our local slice of the Universe. This would result in a 21st century digital 'Hubble Atlas' of nearby galaxies and their surroundings that will provide a standard for testing our understanding of how galaxies attained their present forms and how their stellar components will likely evolve into the future. The resolved and unresolved stellar populations would be analyzed through color-magnitude and color-color diagram fitting, providing accurate and uniform TRGB distances, and through population synthesis modeling of multi-filter broad- and medium-band photometry. The ISM in each galaxy would be observed through key narrow-band filters (Hα, Hβ, [O II], [O III], [S II]; possibly Mg II, [O I], Ca II or [S III]) that allow identifying the ionized gas, estimate its metallicity and variations therein, and for each region determine whether ionization is dominated by photospheric or shock heating. Direct measurements of the extinction toward that ionized gas through the Balmer decrement (Hα/Hβ) will allow measuring the currently ongoing, high-mass star formation in each star formation region.

Key advances in observation needed

Resolution — $\lesssim 0\farcs02$–$0\farcs065$ [300–1000 nm] resolution is required in order to resolve luminous RGB stars out to the distance of the Virgo Cluster, and to resolve the relevant scales for star formation feedback processes within the ISM (shocks, outflows, bubbles, shells) within galaxies.

Wavelength agility — access to both vacuum-UV and near-IR; no wavelength regime alone will suffice for a comprehensive understanding of the star-formation and assembly histories of galaxies.

Wide-field focal plane arrays — these are presently not at sufficiently high TRL; investment is needed to improve yields, provide cheaper devices and high-throughput assembly and testing to enable economies of scale. Such an investment would not just benefit the science proposed here.

Coatings — an investment in improving the relatively poor broad-band performance of optical coatings of telescope mirrors in the UV, with typical reflectances below 85% (Al+MgF_2) and 65% (Al+LiF), directly results in a large increase in throughput for a given telescope aperture, or more affordable missions for a given sensitivity requirement.

Dichroics — most photons collected by telescopes are rejected by bandpass filters. Dichroic(s)

potentially double (or even triple) the observing efficiency of astronomical observatories (e.g., *Spitzer*/IRAC) and allow tuning downstream optics and detectors for more optimal performance, avoiding compromises inherent in forcing performance over more than an octave in frequency.

Enabling science investigations

The proposed science in the present white paper does not stand alone, but must build on a strong understanding of the physics of the star formation process in various environments. Gaining such understanding requires observational detail that can only be attained within our own Galaxy. From that basis one has to step out to galaxies spanning a range of metallicity and star formation activity within our Local Group to provide observational tracers with calibrations that are directly and solidly rooted in physics. We refer the reader to the Science White Paper by P. Scowen et al. "Understanding Global Galactic Star Formation". Also, investment in human capital and in ground-based supporting and path-finding programs, including operational support, should not be ignored, as the overal science return of this and many 'high-end' programs critically depends on it.

Four central questions to be addressed

(1) What is the spatially resolved star formation history of a comprehensive and representative subset of the galaxies encompassed within the local $D < 20$ Mpc volume? To what extent and how does it depend on morphological type class, mass, and cosmic environment? Does this fossil record confirm in detail the broad picture inferred from the evolution of the cosmic star formation density? What does it tell us about the formation and survival rates of solar systems like our own in different galaxies?

(2) What is the mass assembly history of galaxies within the varied cosmic environments encompassed within the local $D < 20$ Mpc volume, the smallest representative slice of the Universe? This overarcing question will likely also include the questions: do galaxies grow from the inside out or is this too simple a picture; and why do galaxy disks have such high angular momenta; and why are they so old?

(3) Can we unravel the true 3-D structure and internal kinematics of galaxy groups and the Ursa Major and Virgo Clusters via reliable TRGB distances and fossil star streams/intra-cluster light? Can we meaningfully constrain how baryons found their way from the IGM into the galaxies, galaxy groups and into clusters of galaxies within the local Universe?

(4) Why does there at least seem to be a dearth of satellite galaxies around the primary galaxies within our Local Group compared to predictions from ΛCDM numerical simulations? Is the Local Group result confirmed throughout the local volume, and if so, what fundamental factor is missing in the simulations?

Area of unusual discovery potential for the next decade

Combination of a large collecting area, very wide field of view, high angular resolution, wavelength agility and/or multiplexing advantage would allow orders of magnitude more efficient UV–optical observations of the star formation and many other processes and, moreover, open up a new domain in discovery space near and far. Injection into L2 (or Earth Drift-Away) orbits allows provide dynamical and thermal stability, and increases (doubling) in efficiency over LEO orbits and, hence, lower cost per hour of observation (all other variables being equal). Large focal plane array

(douzens to hundreds of individual CCD or CMOS detectors) and dichroic camera (simultaneous observation in two or more channels of the same field of view) technology is better matched to the collimated beams provided by optical telescope assemblies and less wasteful in terms of collected photons, maximizing science output and especially benefitting survey science with a lasting legacy beyond the nominal duration of a mission. Survey science allows discovery of very rare objects amongs billions and billions, the positions an properties of which may not be knowable a priori.

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