Response to Solicitation NNH12ZDA008L: Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts

The Crucial Role of High Spatial Resolution, High Sensitivity UV Observations to Galaxy Evolution Studies

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Abstract

Models of galaxy formation and evolution are only as reliable as our knowledge of the individual stars responsible for the light we detect. From the prescriptions for stellar feedback, to numerical simulations, to the interpretation of galaxy colors and spectra, galaxy evolution research depends at its core on reliable star formation and evolution models. These models are calibrated using observations of resolved stellar populations in a wide range of environments. Studies of stellar populations in the UV have made great strides in the past decade with the *GALEX* UV surveys and the UV-sensitive WFC3 camera on *HST*. With the phenomenal data that these instruments have provided, we have learned surprising UV properties of the stellar populations of galaxies and star clusters. While these observations have certainly shed light on the evolution of stars and star clusters, the picture is still far from complete. To fully understand the processes that shape star formation of clusters and OB associations in galaxies with a range of masses, metallicities, and gas content will require the next generation of UV telescopes and instrumentation. To make significant progress, goals for this future instrumentation will need to include improved spatial resolution to resolve individual stars in crowded extragalactic environments and a larger field of view to cover nearby galaxies with fewer pointings. Future observations will then be able to produce the required libraries of resolved stars in carefully selected UV bands to reveal the phyical properties of the stars and properly account for dust extinction. We will detail the instrument requirements for making the necessary observations.

Introduction

In this response, we will discuss the scientific necessity for understanding the details of UV emission from the individual stars that contribute to the integrated light of galaxies and star clusters. Nearly all of the trillions of galaxies in the universe can only be detected through their integrated starlight, even in *HST* (e.g., Coe et al., 2006) or simulated *JWST* images.[1] These faint blobs of light are the luminosity-weighted average emission from the stars that make up those galaxies. To interpret this light therefore requires reliable, well-calibrated models of stars, especially the brightest stars that dominate the luminosity-weighted average. Such models rely on large libraries of photometry and spectra of individual stars (e.g. Bruzual & Charlot, 2003). Such libraries are improving, largely due to *HST*. However, because of the limitations of available telescopes and instruments, the libraries only sample a small fraction of star forming environments, and they contain little UV data. Such incomplete libraries render our interpretation of light from all distant galaxies highly uncertain.

At high-redshift, when the cosmic star formation rate was at its peak ($2<z<4$, e.g., Reddy et al., 2008), the optical light we observe is largely stellar light redshifted from the UV. For the highest redshift galaxies observed ($z\sim8$; Bouwens et al., 2010), the only light we detect is UV emission redshifted to the near infrared. At these redshifts, the UV emission is dominated by young, massive stars. Constraining the physical properties (temperature, mass, age) of these stars is of great interest not only for measuring their contribution to the total light emission from the galaxy, but also for constraining their effects on the surrounding interstellar, and potentially intergalactic, medium.

In addition to the importance of UV observations for measuring the effects of star formation and massive stars on the evolution of galaxies, UV observations have also proven incredibly sensitive to the evolution of old, low-mass stars. In particular, with resolved UV photometry of old stellar populations, we have begun to constrain the evolution of stars through the hot horizontal branch, including short-lived, UV-bright phases of evolution that can significantly affect the UV luminosity of galaxies and are relevant to the yield of chemical elements. Furthermore, this UV-sensitivity has proven itself capable of constraining generations of stars at very old ages (>10 Gyr), something that was not possible with optical data alone.

In nearby galaxies and star clusters, the UV flux can be resolved into individual stars. An example of this resolving power is shown in Figure 1. The two panels show the same region in M31 as observed by *GALEX* (left) and UVIS on *HST* (right). With the high-resolution *HST* image, it is clear that the *GALEX* emission comes from individual hot stars. These stars are excellent analogs of the stars responsible for the UV light we observe from more distant galaxies and star clusters, and therefore offer our most precise constraints on and reliable tests of the mass and age distributions inferred from the light observed in distant systems.

The fact that most UV emission from galaxies is from stars may not be surprising, but unfortunately, very few of these stars have actually been studied in the UV. The lack of observational constraints makes the interpretation of integrated light difficult. We will now discuss the advantages of UV observations of young and old stellar populations in detail, showing that resolving individual stars in the UV is crucial for the advancement of near-field, as well as, high-z cosmology.

Massive Stars

The evolution of galaxies is strongly affected by the process of star formation. During their

[1] http://www.stsci.edu/jwst/science/simulations/

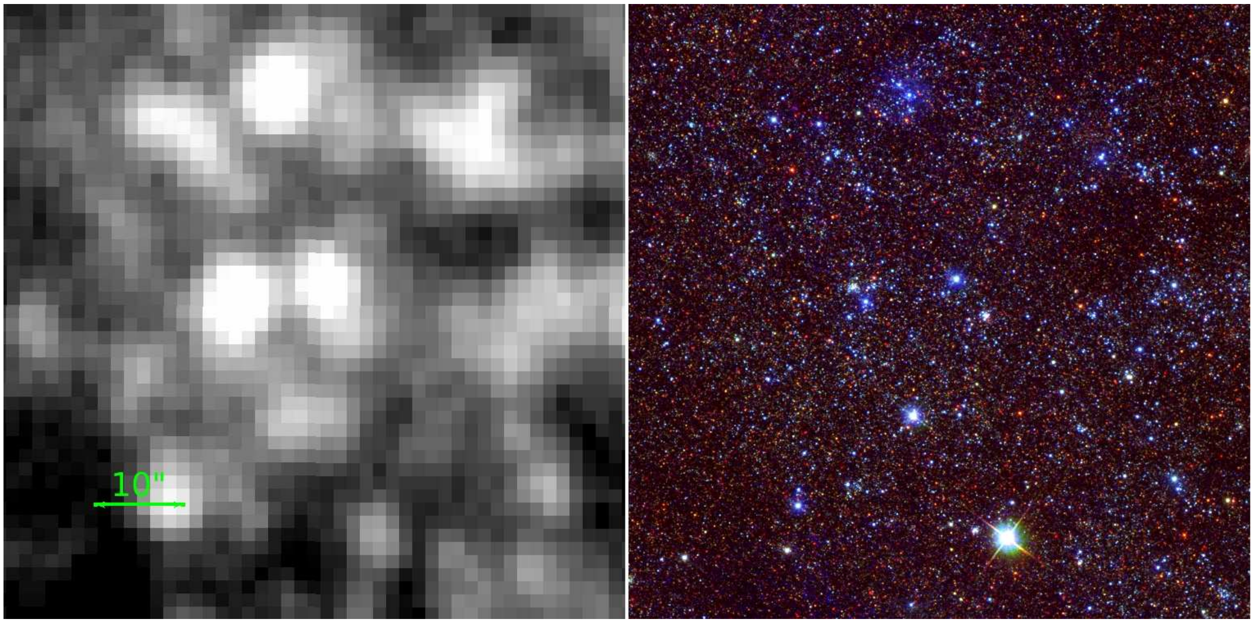

Figure 1: *Left: GALEX* NUV image of a UV bright portion of the M31 disk. *Right: HST* UVIS image of the same region (blue=UV, green=V, red=I). The UV emission detected by *GALEX* clearly originates from bright blue stars.

short lifetimes, high-mass stars produce ionizing radiation, powerful stellar winds, supernova explosions, and heavy elements. All of these processes contribute significantly to the movement, temperature, pressure, and chemistry of the gas in the galaxy potential. The fate of this gas — whether it escapes the galaxy, forms a hot halo, or cools and forms more stars — fundamentally shapes the evolution of the galaxy.

Massive stars provide most of the rest-frame UV radiation we observe, which is then used to infer fundamental properties, such as the initial mass function (IMF) and star formation rates. The utility of UV measurements is crucial, but must be calibrated using large samples of individual massive stars in a variety of environments.

The UV as a Probe of Star Formation

UV flux has long been considered an indicator for the star formation rate in galaxies (Salim et al., 2007). These rates require reliable models of the UV flux from massive stars and proper dust-extinction corrections. However, because of the scant available UV data of massive stars, currently limited to the Milky Way and Magellanic Clouds, these models suffer from significant deficiencies. When the models are tested with measurements of resolved stars in other nearby galaxies, significant systematic errors appear (see Figure 2). Not only is too much UV flux predicted, it is also bluer than what is actually observed.

The resulting errors in predicted UV fluxes point to clear deficiencies in the current models of massive stars, which have far-reaching impacts on the interpretation of the light from distant galaxies. A comprehensive library of massive star UV fluxes covering as many galaxy types as possible is necessary to provide the best calibration of these models. Such a library would be well-served to include high SFR galaxies like NGC 253 and M82, as well as all nearby dwarf galaxies. Such observations require higher spatial resolution and UV sensitivity than *HST*.

Distinguishing Temperature and Dust Effects

Only with UV observations of individual stars is it possible to separate the effects of

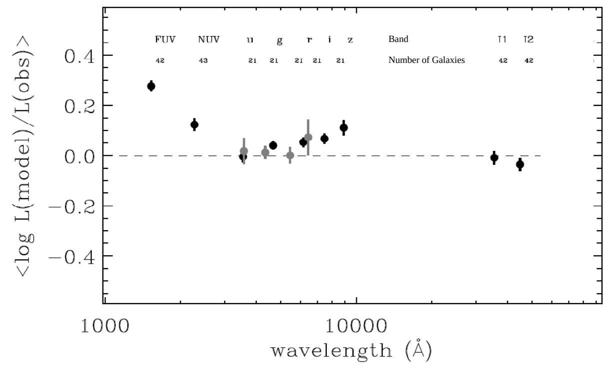

Figure 2: Residuals of observed vs. modeled SEDs for star-forming dwarf galaxies (B. Johnson et al. in preparation). Models derived from star formation rates determined from *HST* resolved stellar photometry do an excellent job of predicting the integrated fluxes in the optical and stellar-dominated NIR bands, but fail dramatically in the UV.

temperature and dust reddening, allowing reliable measurements of stellar temperature and radii. This ability is shown in Romaniello et al. (2002) and more recently in Bianchi & Efremova (2006); Bianchi et al. (2011, 2012) The spectral energy distributions (SEDs) of massive hot stars are indistinguishable in the optical data alone. However, when UV data are included in the SED, a reliable temperature and extinction can be measured (and luminosity, mass, and age inferred).

Such studies of resolved young stellar populations in nearby environments allow us to quantify the star formation process. For example, we can measure the spatial scales and hierarchical clustering of young stars, revealing the effects of dynamical evolution. An example of this from the *HST* M31 multicycle treasury program (Dalcanton et al., 2012) is shown in Figure 3, where the temperatures and radii of thousands of stars measured by this technique are shown spatially for a section of M31. Hotter (younger) stars are more spatially clustered.

Finally, the extinction measurements for each star probes the structure of the dust cloud, quantifying the dust distribution and the reprocessing of UV light from massive stars into IR light from warm dust. These quantitative constraints on the massive star content are only possible with wide-field ($>10'$), high spatial resolution ($<0.1''$) imaging in the UV, which provide the necessary data for a large enough number of stars over a sufficiently large portion of the galaxy to probe environmental effects on the star-formation process.

The Initial Mass Function

Future UV observations of extragalactic massive stars are critical to our measurement of one of the most fundamental relations in astrophysics, the initial mass function (IMF). The IMF provides the foundation for the interpretation of photometry and spectroscopy of galaxies. For example, one must assume an IMF to calculate the amount of stellar mass that is represented by the UV light observed in from a galaxy. Unfortunately the high-mass end of the IMF, which has the most impact on the interpretation of the luminosity-weighted fluxes we observe, remains highly uncertain (Kroupa, 2001; Bastian et al., 2010, Weisz et al. ApJ, submitted). In fact, it is not yet clear if the IMF is a strong function of environmental properties, such as metallicity and star formation rate, or is universal (Bastian et al., 2010).

The lack of knowledge about the high mass IMF is largely due to a lack precise mass measurements of high-mass stars, and the most precise masses are provided by UV data. Reliable temperatures, as measured using the methods described above, can be converted to luminosities and masses using well-constrained scaling relations. These masses can then be analyzed to constrain the high-mass IMF. With our copious *HST* data on M31, we will likely gain knowledge of the IMF *in this one system*. We will need data in more, and different, systems to put tight constraints on universality.

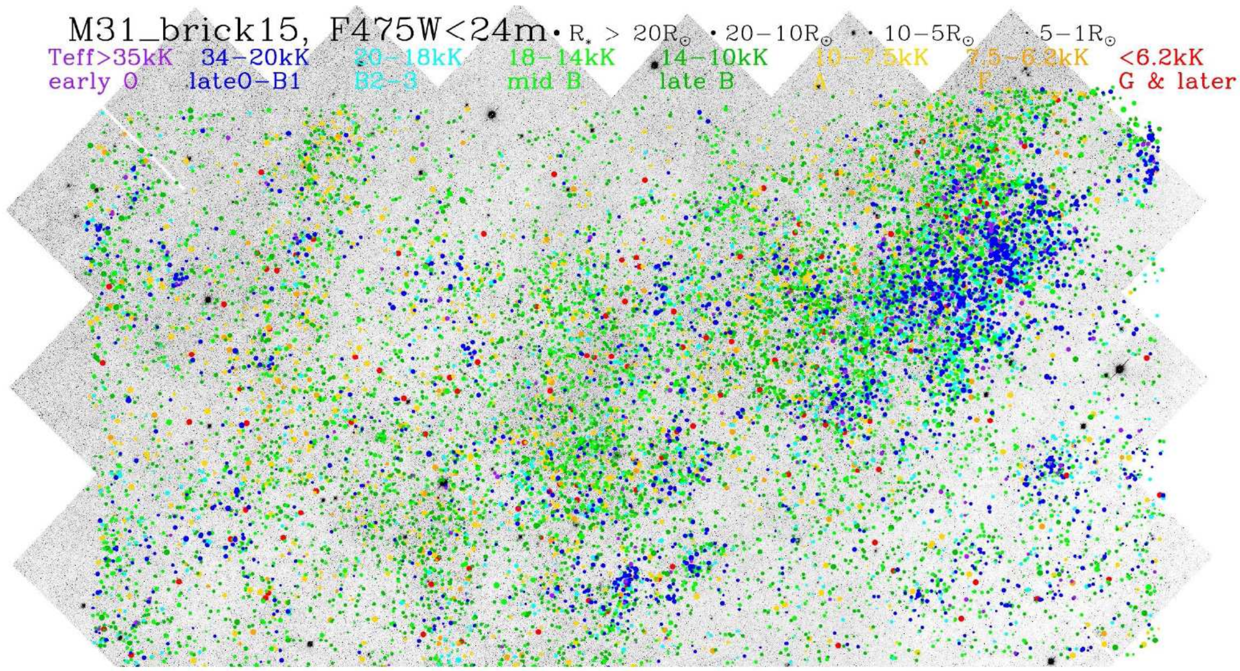

Figure 3: The locations of massive stars over a $12' \times 6'$ area of the M31 disk. Colors indicate temperature; point size indicates radius (Bianchi et al., in preparation).

Low Mass Stars

Although massive stars are usually thought to be the only sources of UV emission, low-mass stars also evolve through UV-bright phases that can significantly affect the integrated UV flux. This issue goes back to the earliest UV observations ever made. The Orbiting Astronomical Observatory observed the bulge of M31 in the UV for the first time. The M31 bulge was expected to be UV faint because it is dominated by old stars. Instead, significant flux toward shorter wavelengths was detected (Code, 1969). M32, another old system, also shows such a UV-excess, along with many other non-star-forming early type galaxies (e.g Burstein et al., 1988).

Short-lived, UV-Bright Evolutionary Stages

Thanks to *HST*, we now have the ability to resolve some of the UV emission from the M31 bulge and M32 into individual stars (Brown et al., 2000; Rosenfield et al., 2012). The stars responsible for the bulk of the UV light from old populations are now known to be extreme horizontal branch (EHB) stars (O'Connell, 1999; Brown et al., 2000). However, we only cleanly resolve the bright end of the UV-bright populations in the M31 bulge and M32 with the current instrumentation. These brightest stars are the post-HB stars, not the much more numerous EHB stars responsible for the bulk of the UV flux, which cannot currently be probed directly.

Even without resolving the EHB population itself, progress has been made. For example, a correlation between EHB production and metal abundance is clear, both in galaxy samples (Burstein et al., 1988; Bureau et al., 2011) and within M31 (Rosenfield et al., 2012), providing constraints on evolution theories that produce these EHB stars. Furthermore, the UV-excess appears to decrease with redshift (Ree et al., 2007), consistent with its association with very old populations. A handful of these stars have been studied in detail in our Galaxy (Busso et al., 2005); however, detailed observations of a large sample will require the next generation UV telescope to have higher sensitivity and spatial resolution than *HST*.

Detailed Abundance Sensitivity

The UV spectral range is well-known to contain a very dense forest of features from metals and molecules. The number of features in the UV is so dense that the SEDs of metal-rich stars are redder due to "line-blanketing," a term used to describe the cumulative effect of many absorption features significantly depressing the broadband UV flux. Thus, the UV properties of stars are very sensitive to their abundance characteristics. *These spectral features cannot be observed through the Earth's atmosphere,* so that without UV capability in space, such areas of research will be completely lost. This sensitivity has allowed the UV to be used to separate multiple stellar populations in systems that traditionally have been considered single population systems: globular clusters.

For example, deep resolved UV stellar photometry of the globular cluster 47 Tuc reveals two separate sequences of stars corresponding to two generations, both ancient, but with differing chemistry. The first generation is nitrogen-poor, while the second is nitrogen-rich. Because the UV contains a strong nitrogen-sensitive absorption feature, the UV photometry easily separates the two previously-unidentified populations (Milone et al., 2012). The separation of the stars into their separate generations allows the robust measurement of the fraction of stars from each. In 47 Tuc, the second generation dominates everywhere in the cluster and is more centrally concentrated than the first.

These quantitative measurements of processes that occurred more than 12 Gyr ago were made possible by high spatial resolution, high sensitivity UV observations, and require a UV-sensitive telescope in space. 47 Tuc is one cluster among hundreds in our Galaxy, and those in our galaxy do not well sample a wide range of ages and metallicities. Performing such detailed studies on the younger and more metal-rich globular clusters in M31 (and some of the younger and lower metallicity clusters in M33) for example, would provide a significant leap forward in our understanding of the formation of globular clusters under more diverse conditions.

Technical Goals

We are currently barely capable of resolving the stars of interest in the Local Group (<1 Mpc). The limits are due to spatial resolution. At *HST* resolution, young stars in galaxies outside of the local group blend together, which does not allow us to measure the properties of the individual stars. Spatial resolution better than that of *HST* is therefore require to make measurements outside of the Local Group.

The next mission would fundamentally improve our available libraries of resolved stars if one of its goals were to resolve the stars of interest in the nearest galaxies with star formation rates comparable to those at high-redshift. These are NGC 253 (Engelbracht et al., 1998) and M82 (Telesco, 1988), at distances of ∼4 Mpc. A new regime in observational experiments can be reached with a diffraction limit roughly a factor of 4 better than that of *HST*, *i.e.*, an 8–10 meter UV/Optical space telescope.

Furthermore, field of view is of great importance. For example, the M31 multicycle treasury program will spend 828 orbits to map a large portion of the disk; this program could be completed in 8 orbits if the ACS and WFC3 fields of view were 100 times larger at the same spatial resolution. Such a prospect requires very large numbers of pixels and the ability to store and dump the very large images required. On the ground, cameras with more than 100× the current number of UVIS pixels are under construction (Gilmore et al., 2012), suggesting such a large increase in field of view may be possible for the next generation of space telescopes. Such an increase would boost the productivity of the observatory by two orders of magnitude.

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