Massive Stars: Stellar Populations

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ABSTRACT

Massive stars dominate the chemical and dynamical evolution of the ISM, and ultimately of their parent galaxy and the universe, because of their fast evolution and intense supersonic winds. Four decades ago, the first rocket UV spectra of massive stars revealed the importance of mass loss and began to change our understanding of their evolution. Recently, advances in stellar modeling, and the observation of crucial ions in the far-UV spectral range, led to the resolution of long-standing issues in our understanding of massive star atmospheres. A revised (downwards) calibration of $T_{\rm eff}$ for early spectral types is emerging as a result. Meanwhile, HST imaging, and large ground-based telescopes with multi-slit spectroscopic capabilities, had opened the possibility of resolved studies of stellar populations in Local Group galaxies, which sample a variety of metallicity and environment conditions. More recently, GALEX is providing a global, deep view of the young stellar populations for hundreds of nearby galaxies, revealing their recent star-formation history and modalities. The wide-field coverage and sensitivity of the GALEX UV imaging, easily detecting extremely low levels of star formation, is again changing some of our views on massive star formation in galaxies.

Key words: massive stars, stellar parameters, stellar populations, nearby galaxies

1. Introduction

Massive star populations trace the recent star formation in galaxies. Their study allows us to understand the modalities of the star-formation process and the role of metallicity and other environmental characteristics, as well as the interplay between massive stars and evolution of the surrounding interstellar medium (ISM). Massive stars are bright, especially at UV wavelengths, so they can easily be observed in distant galaxies. They are short-lived, therefore they provide a snapshot of current and recent star formation unconfused by prior star-formation history. They enrich the ISM of heavy elements, processed during their fast evolutionary time-scales, and returned to the ISM during intense mass-loss phases and supernova explosions. Finally, they influence the kinematics and ionization of their parent cloud via supersonic winds during their main sequence and W-R phases, and outflows and explosions in the final evolutionary phases.

The physical characterization of the stellar constituents of star-forming complexes in galaxies of the Local Group, which span a large factor in metallicity and a broad variety of galaxy types and conditions, is currently possible with several instruments offering high resolution imaging. One advantage of studying stellar populations in a galaxy of the Local Group is that all the stars are at approximately the same, known distance, so their absolute luminosity can be derived and physical Hertzprung-Russel diagrams (HRD) can be constructed, and yet they are close enough that the stars can be resolved and measured accurately.

HST imaging in particular is still unsurpassed for studies targeting hot stars, because of its angular resolution and broad wavelength range, from the UV to the IR. The inclusion of UV bands is a powerful way to select the most massive, hottest stars, to whose high temperatures the optical colors are insensitive (e.g. Massey et al. 2003, Bianchi & Efremova 2006).

Four decades ago, the advent of space-born UV spectroscopy marked the discovery of mass loss in massive stars and began to change our understanding of their evolution. More recently, significant advances in stellar modeling, and the observation of crucial ions in the far-UV spectral range disclosed by FUSE, allowed us to resolve long-standing issues in the modeling of massive stars' expanding atmospheres, and to assess of the roles of shocks and clumping in the stellar winds. A related paper in this book (Bianchi, Herald, & Garcia, 2006) describes recent advances in the measurement of the physical parameters of massive stars from spectroscopy. From such detailed spectroscopic analyses of individual stars a new calibration of stellar parameters versus spectral type is emerging. Here I address the study of massive star populations from photometry of resolved OB associations, star-forming regions, and stellar clusters in nearby galaxies (section 2 and 3), and from the wide-field, deep UV imaging provided by GALEX (section 4).

When considering what would be most useful to include in this paper, I decided to devote most of the allocated pages to highlighting some aspects of the methods used in the study of massive star populations, and in particular the advantage of using UV data. I also chose to include in some detail selected, surprising results from the GALEX Nearby Galaxies Survey, which open new questions and call for future thoughts and observations. Therefore, this paper is biased towards UV methodology, and open questions, rather than giving a balanced and comprehensive overview of recent results, since these abund elsewhere.

2. Characterization of the young stellar populations and the massive star content in Local Group galaxies

High resolution imaging of star-forming regions in several bandpasses allows us to characterize the age of young associations and their massive star content, by constructing HR diagrams and comparing them to evolutionary tracks. Usually, the photometry of the stars is translated into physical parameters by comparing the observed colors to model colors or empirical calibrations. In addition to the effective temperature, extinction by interstellar dust affect the observed colors, therefore this parameter must be derived concurrently with the stellar physical parameters. I recall briefly some of the methods generally used, and emphasize in particular the advantage of using UV bands in addition to optical bands, for the characterization of the hottest stars. Optical colors are insensitive to hot temperatures but UV colors can unambiguously detect the earliest types (e.g. Massey 2003, Bianchi & Efremova 2006, Bianchi & Tolea 2006). This can be appreciated at a glance in Figure 4. Quantitatively, we show in Figure 1 the variation of reddening-free indices constructed from different colors, with effective temperature. The indices are constructed from model grids, which are described e.g. in Bianchi et al. (2006). Because some of today's most useful instruments for these studies are the HST imagers (ACS and WFPC2 in particular, which include UV and optical filters), we show in Figure 1 the sensitivity to $T_{\rm eff}$ of sample colors constructed in the bandpasses of some HST imaging filters.

The "reddening-free index" (Q) is commonly used to derive $T_{\rm eff}$ and E(B-V) when at least three photometric bands are available. It was traditionally defined, and mostly used, with the U,B,V bands, but it is applicable to any combination of three filters:

$$Q_{UBV} = (U-B) - \frac{E(U-B)}{E(B-V)}(B-V) = (U-B)_0 - \frac{E(U-B)}{E(B-V)}(B-V)_0 = Q_{UBV0},$$

The above equation is true only in the parameters range where the ratio $C = \frac{E(U-B)}{E(B-V)}$ is actually constant. For $T_{\rm eff}$ lower than $\approx$ 10,000 K (and for very high extinction values), Q is multivalued, and C is no longer constant, therefore Q is not reddening-free, and the method is not applicable (see Bianchi & Tolea 2006, Bianchi & Efremova 2006 for a detailed discussion). Figure 1 shows that inclusion of UV bandpasses in the Q index provides greater sensitivity to the hottest temperatures.

When photometric measurements in more than three bands are available, $T_{\rm eff}$ and E(B-V) are best determined by χ^2 fitting of all available colors with model colors (see examples in Figure 8 of Bianchi & Efremova, 2006, and Figure 5 of Bianchi, Efremova et al. in this book).

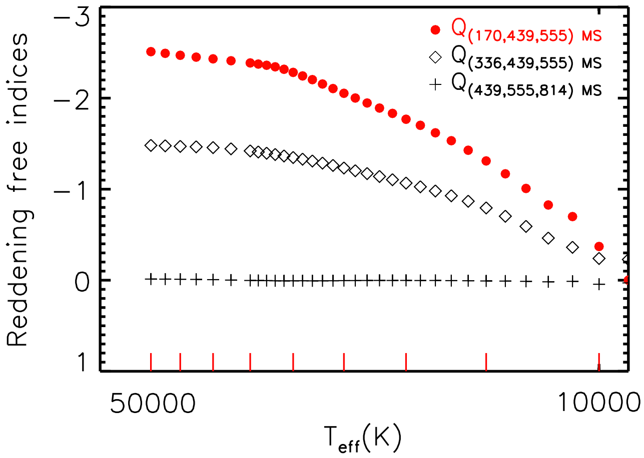


Figure 1: The reddening-free index Q constructed from stellar model colors, for three sample combinations of HST-WFPC2 filters. The plot shows the sensitivity of different filter combinations to $T_{\rm eff}$. The range for $T_{\rm eff} < 10000$ K is not shown, because the indices are no longer reddening-free, and the solutions are not unique (e.g. Bianchi & Tolea, 2006, Bianchi & Efremova 2006). Above 10000 K, colors are not sensitive to gravity, so only models for main sequence stars (MS) are shown. The combination of F336W, F439W, F555W represents the classical Q_{UBV}. An index including the U-band begins to resolve blue stars, a UV filter allows to distinguish stars with $T_{\rm eff}$ between 25000 K and 50000 K.

3. Young stellar clusters

The stellar cluster systems of galaxies provide information about the star-formation history of their galaxy. Each cluster represents a single age, single metallicity, population, giving information on the star-formation process. Integrated photometry of clusters in nearby galaxies can be compared to simple stellar populations (SSP) models to derive cluster age and extinction, hence cluster mass from the extinction-corrected luminosity and age. Young massive clusters are best studied from their UV colors, as shown in figures 2 and 3 (see also e.g. Bianchi et al. 1999), Chandar et al. 1999), Bianchi et al. 2005).

4. GALEX Nearby Galaxies Survey

GALEX (The Galaxy Evolution Explorer) is a NASA Small Explorer (SMEX) mission, performing spectroscopic and imaging surveys of the sky in the space ultraviolet (Martin et al. 2005). GALEX imaging is performed simoultaneously in two broad

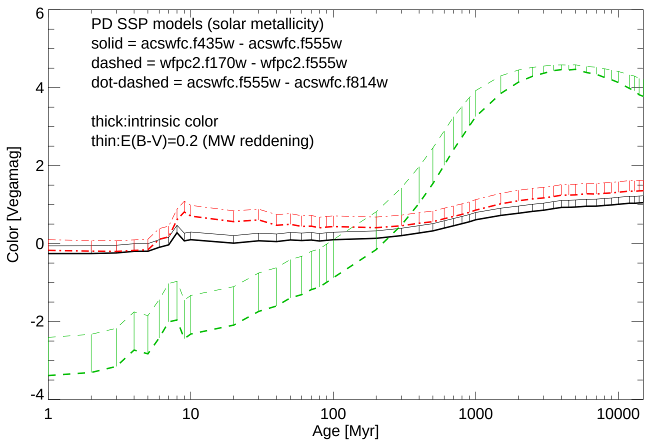


Figure 2: Theoretical colors for stellar clusters as a function of age, for sample ACS and WFPC2 filters. The broad wavelength baseline from UV to V gives greater sensitivity to the younger ages. UV bands are more sensitive to extinction as well.

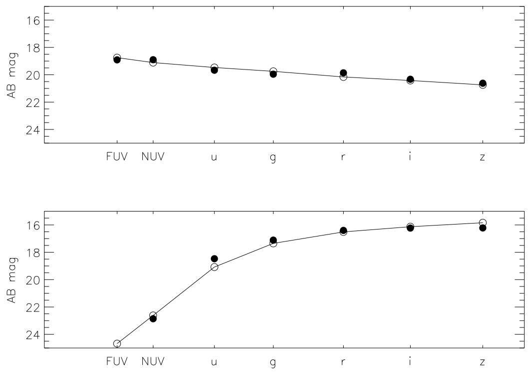


Figure 3: The UV−*to*−IR SEDs of two sample star-forming complexes in M101 (GALEX far-UV and near-UV, SDSS u, g, r, i, z photometry, filled dots) and the best fit SSP model (empty dots connected by a line). From the fit we derived ages of 4 Myrs (top) and 6 Gyrs (bottom) respectively (from the work of Bianchi et al. 2005). $E(B-V)$ was derived concurrently in the fitting process. The two UV bands are decisive in resolving young ages.

bands, far-UV (FUV, 1344 - 1786 Å, λ_{eff} = 1528 Å) and near-UV (NUV, 1771 - 2831 Å, λ_{eff} = 2271 Å) (Morrissey et al. 2005).

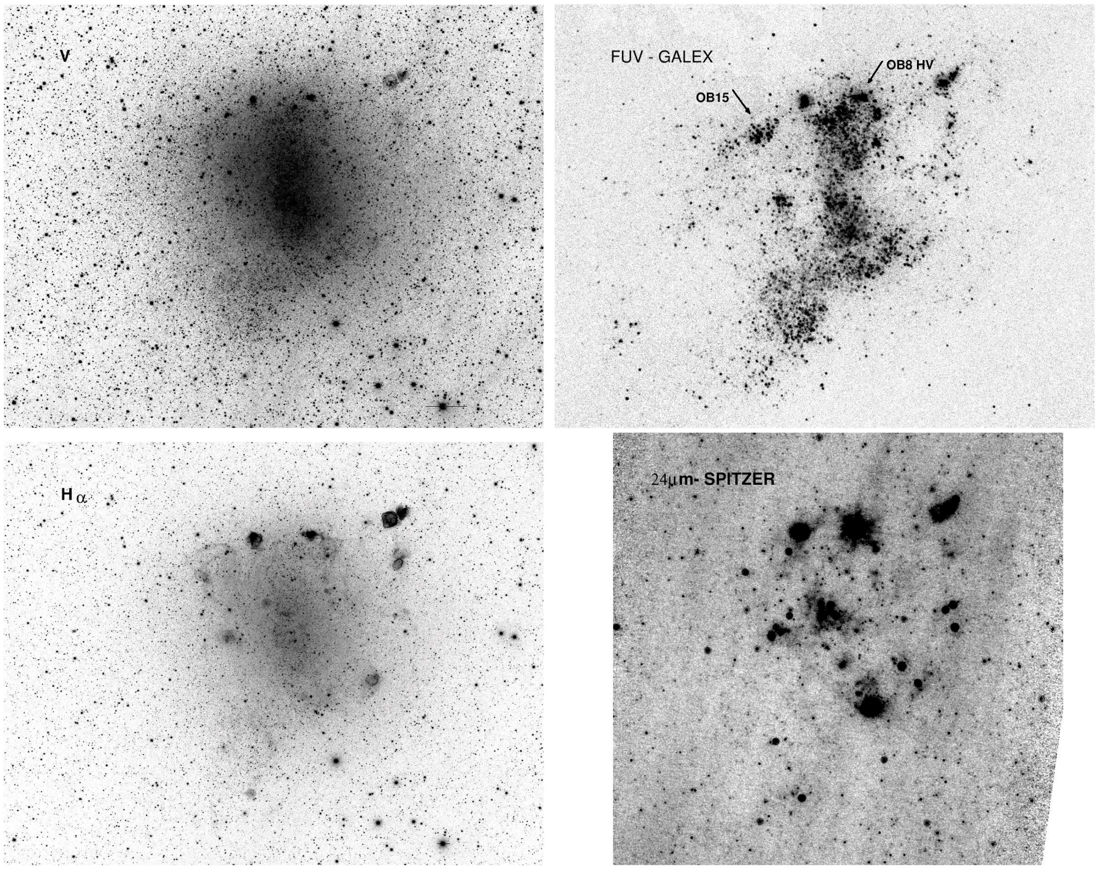


Figure 4: The Local Group galaxy NGC6822 in four bands: the V-band shows the global stellar population, the GALEX FUV-band shows the regions of recent and current star formation (massive stars unobscured by dust), the Hα image shows the gas ionized by the most massive stars, and the SPITZER 24μ image shows regions of star formation embedded in heated dust. The two star-forming regions OB15 and Hubble V are indicated. Their color-magnitude diagrams are shown in the next figure. The V-band and Hα images are taken from the NOAO survey (Massey et al. 2006).

A dedicated survey of nearby galaxies (NGS) is being performed, and almost completed, deeper than the all-sky map. The GALEX large field of view (1.2°) afforded complete coverage for large Local Group objects. These data provide a snapshot of recent high-mass star formation across entire galaxies, allowing for the study of

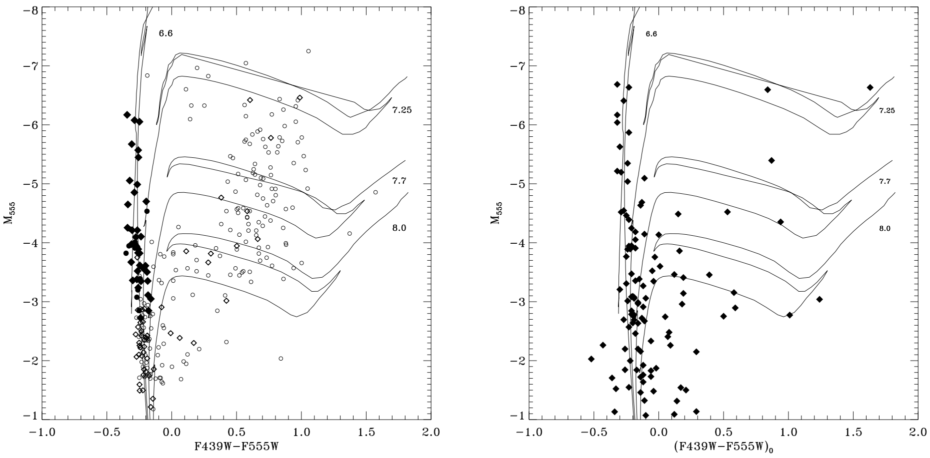


Figure 5: Color-magnitude diagrams of two star-forming regions in NGC 6822: OB15 (left, from Bianchi & Efremova 2006, HST-WFPC2 photometry) and Hubble V (right, combining HST STIS and WFPC2 photometry from Bianchi & Efremova 2006, and Bianchi et al. 2001). Diamonds are stars in these two regions, filled symbols are stars also detected in UV filters. Other symbols are the outer field population. Isochrones (ages marked in log [years]) are from Padua evolutionary models (Girardi et al. 2002).

rest-frame UV morphology, spatial variations of the local SFR, and extinction. The GALEX NGS is complemented by datasets at other wavelengths, to study the stellar populations and the gas content.

Specifically, the UV emission traces the young stellar populations (younger than a few hundred million years) unobscured by dust, and down to extremely low levels of star formation. IR imaging provides a complementary view of the extremely young, dust-embedded regions of intense star formation (see figure 4). Hα imaging, another classical tracer of star formation, is only sensitive to the presence of the most massive, youngest stars, hence probes much shorter time-scales (younger ages) than the UV emission. In addition, the Hα emission strongly depends on the density of the surrounding medium, and on the structural properties of the ionizing star cluster. The combination of these three star-formation tracers provides a complete census of the current star formation in galaxies. The example of the small irregular galaxy NGC 6822 is shown in figure 4. Two OB associations in this galaxy, OB 15 and OB 8 in the bright HII region Hubble V, have been studied with multi-band HST photometry. Their color-magnitude diagrams (Figure 5) and HR diagrams (Bianchi et al. 2001, Bianchi & Efremova 2006) indicate similar ages and massive star content. However, OB 8 is a strong Hα and IR emitting region, and OB 15 is not. While the two associations seem to have similar massive star content, they differ in their spatial concentration (OB 15 is much less compact than OB 8), and possibly in their dust properties. However, a small difference in the cluster ages, which could elude the photometric characterization, and will be investigated with follow-up spectroscopy, may also cause the difference in Hα emission.

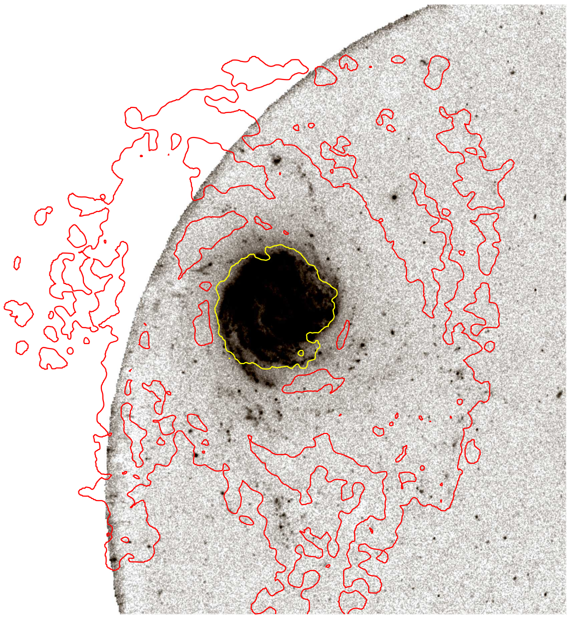
The original GALEX NGS sample comprises a few hundred nearby galaxies selected both for specific science goals and for complementarity with other planned or on-going surveys at longer wavelengths, including SIRTF's Legacy and GTO observations, multiple ground-based surveys at Hα (PO/LCO, STARFORM), and at radio wavelengths (WSRT SINGS, BIMA SONG). The current GALEX database includes over 4000 galaxies with $D_{25} > 1'$; about half are observed at a depth greater than the All-sky Imaging Survey (AIS).

An atlas of 1034 GALEX NGS galaxies observed in the first half of the mission, with exposures of one GALEX orbit or more, is published by Gil de Paz et al. (2006a). Early results from studies of individual galaxies are in the press (e.g. Bianchi et al. 2005, Thilker et al. 2005, Calzetti et al. 2005, Thilker et al. 2006). Other related papers can be found in a GALEX dedicated ApJL issue (2005, Vol. 619), containing the early results, and an ApJ Supplement dedicated issue (in press).

4.1. Massive star formation in extreme environments. XUV-disk galaxies

One of the most surprising early results from the GALEX NGS, which is changing some of our previous views on star formation, is the discovery of consipcuous UV emission extending up to a few times the optical radius (R_{25}) in some spiral galaxies. First discovered in M83 (Thilker et al. 2005) and NGC4625 (Gil de Paz et al. 2005), the UV emission appears mostly as spiral-arms structures (suggesting a disk geometry) stretching far beyond the extent of the galaxy as traced by HII regions and optical light (figure 6). The UV emission indicates that recent and/or current star formation is occurring in these outer regions, which were previously believed to be stable against star formation because of their gas surface density significantly lower than the traditionally accepted threshold ($\Sigma_{gas} <$ 5-10 $\dot{M}$pc^{-2}, Kennicutt 1998). The discovery of star-formation activity where the azimuthally averaged gas surface density is > 1 dex below the star-formation threshold, indicates that in such low column density environments star formation (and its modalities, and threshold) must be understood and quantified in terms of local conditions.

Except for a work by Ferguson et al. (1998) which noted faint, isolated HII in three galaxies from their Hα wide-field imaging survey, such very extended disks were unreported from studies at other wavelengths prior to the GALEX discovery. We have now discovered a few dozen "XUV-disk" galaxies, i.e. spiral galaxies showing UV emission significantly extending beyond the optical radius, in our current NGS sample of a few hundred nearby galaxies (Thilker et al., in preparation). The NGS team obtained deep Hα and broad-band optical imaging from several follow-up programs involving larger teams. In most of the cases studied, as in our XUV-disk prototypes M83 and NGC4625, the Hα radial profile has a sharp decline ("edge") at a radius



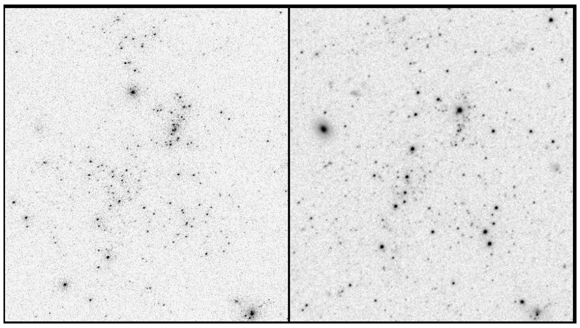


Figure 6: The GALEX FUV image of M83 (top) showing outer spiral arm-like structures extending a few times beyond the optical radius. The R_{25} radius is indicated by the Toomre limit (yellow/light contour). In red/dark are HI contours. Figure adapted from Thilker et al. (2005). In the bottom panel, HST-ACS imaging of one of the Southern bright sources in the XUV-disk, in UV (left) and optical bands (right), The top image is 44′ on a side; the ACS SBC images are 27″ on a side, they cover just one small spot of the XUV-disk in the GALEX image.

consistent with the star-formation threshold, as estimated from the classical criteria (Kennicutt 1989, Martin & Kennicutt 2001, Hunter et al. 1998). By contrast, UV-light profiles show no "edge", in spite of the much smaller area coverage of the "XUV-disk" structures in comparison to the inner spiral arms (figure 7). The general lack of conspicuous HII regions accompanying the XUV-disk emission, and the fact that the phenomenon is not ubiquitous (only a fraction of the spiral galaxies in the GALEX NGS are "XUV-disk" galaxies), poses new interesting questions. Is the IMF modified (e.g. truncated) in such low density environments? Or does star formation occurr only in form of low mass clusters so that stocastic effects dominate? Or is the low gas density favouring substantial photon leakage? The FUV-NUV color indicates the presence of populations younger than a few hundred million years, and in some cases it becomes bluer outwards, suggesting a progressively younger stellar populations and/or lower metallicity in the outermost regions. In these objects we are clearly witnessing the progressing of disk formation, which provides new clues to understand galaxy formation. Are the different XUV-disk morphologies observed in our sample providing snapshots of different phases of the disk formation? or, are XUV-disks episodical, caused by interaction events (this seems to be the case in some of the objects, but not all) enhancing infall?

While XUV-disk galaxies show commonalities, our sample extracted from the current GALEX NGS data shows a variety of morphologies, intensity and surface coverage of the XUV emission. However, morphologies fall in two main types of XUV-disks: one class displays filamentary, spiral-arm-like structures, usually very extended, and little emission outside the spiral arms, and another class shows flocculent and diffuse UV emission surrounding the inner (optical) main body of the galaxy (Thilker et al. 2006, in preparation).

Models of galaxy chemical evolution (Chiappini et al. 2003, Boissier et al. 2001) predict that modest SFR and gas infall variations in outer disk regions would significantly affect abundance gradients. Spectroscopy with Magellan-I for a few UV-emitting regions in our two protoytpe XUV-disk galaxies, indicated metallicity values of $0.1Z_\odot$ or less, but also variations, in the outer disks (Gil de Paz et al. 2006b).

Bianchi et al. (2006, in preparation) have analyzed SEDs of the compact star-forming regions in the GALEX FUV and NUV images and in five optical bands, for two XUV-disk galaxies, and found that the younger sources both in the outer disks and in the inner galaxy tend to have smaller masses than older clusters, with SF complexes in the outer disks having extremely small masses. GALEX's wide field-of-view and sensitivity was ideal for the discovery and morphological characterization of XUV-disks out to several D_{25} radii. However, the GALEX $\approx 5''$ resolution probes a scale of $\approx$ 150pc at a typical distance of 6Mpc, and only large UV-bright complexes are measured. To understand the nature of the XUV-disk emission, we used HST-ACS imaging (Figure 6) to resolve some of the GALEX XUV-disk sources. The data show the UV emission to originate from sparse small clusters or individual stars. The HST resolution provides photometry of the resolved sources and determination of their physical parameters, but only a few extremely small regions centered on the brightest UV-emission peaks can be observed with HST. Questions such as the possible existence of a diffuse emission component, and of a gradient in the stellar population (and/or extinction), remain to be answered and need to be addressed with future instrumentation.

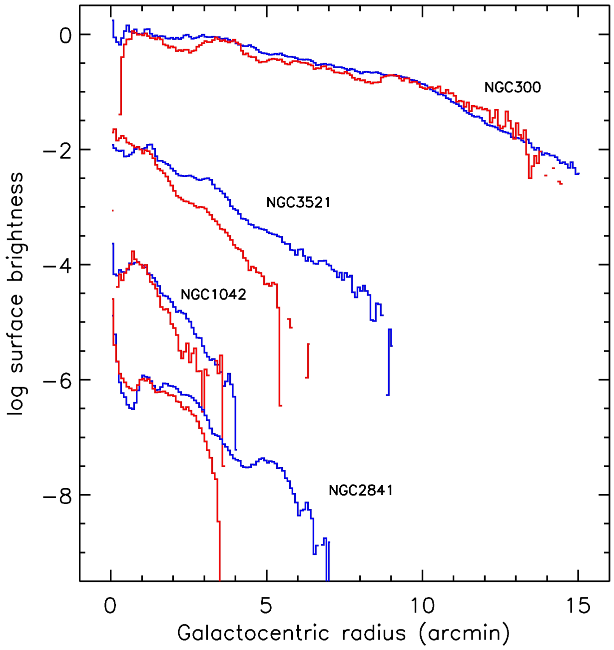


Figure 7: Radial profiles in the FUV (blue/dark) and Hα (red/light) for sample NGS galaxies. The profiles have been arbitrarily offset in flux for clarity; the Hα profile has been scaled to match the FUV profile at $1'$ galactic radius. In XUV-disk galaxies (e.g. NGC 2841) the Hα light profile has a sharp drop, in contrast with a smooth decline of the FUV light. In non XUV-disk galaxies (e.g. NGC 300), Hα and FUV profiles match (see Thilker et al. 2006).

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