NEW CONSTRAINTS ON THE STAR FORMATION HISTORIES AND DUST ATTENUATION OF GALAXIES IN THE LOCAL UNIVERSE FROM GALEX

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ABSTRACT

We derive a variety of physical parameters including star formation rates (SFRs), dust attenuation, and burst mass fractions for 6472 galaxies observed by the Galaxy Evolution Explorer (GALEX) and present in the Sloan Digital Sky Survey Data Release 1 (SDSS DR1) main spectroscopic sample. Parameters are estimated in a statistical way by comparing each observed broadband spectral energy distribution (SED) (two GALEX and five SDSS bands) with an extensive library of model galaxy SEDs, which cover a wide range of star formation histories and include stochastic starbursts. We compare the constraints derived using SDSS bands only with those derived using the combination of SDSS and GALEX photometry. We find that the addition of the GALEX bands leads to significant improvement in the estimation of both the dust optical depth and the star formation rate over timescales of 100 Myr to 1 Gyr in a galaxy. We attain sensitivity to SFRs as low as 10^{-3} M_\odot yr^{-1}, and we find that low levels of star formation (SF) are mostly associated with early-type, red galaxies. The least massive galaxies have ratios of current to past-averaged SF rates (b-parameter) consistent with constant SF over a Hubble time. For late-type galaxies, this ratio on average decreases with mass. We find that b correlates tightly with NUV − r color, implying that the SF history of a galaxy can be constrained on the basis of the NUV − r color alone. The fraction of galaxies that have undergone a significant starburst episode within the last 1 Gyr steeply declines with mass, from ~20% for galaxies with ~10^{8} M_\odot to ~5% for ~10^{9} M_\odot galaxies.

Subject headings: galaxies: evolution — galaxies: fundamental parameters — galaxies: starburst — ultraviolet: galaxies

1. INTRODUCTION

Modern large-scale galaxy surveys are allowing us to place new constraints on the history of star formation (SF) in galaxies. High-quality optical spectra collected by the Sloan Digital Sky Survey (SDSS) have been used to study the recent star formation histories, dust content, and metallicities of over 10^{3} nearby galaxies (e.g., Kauffmann et al. 2003a, 2003b; Brinchmann et al. 2004; Tremonti et al. 2004). These analyses make use of specific absorption and emission lines in the galaxy spectra and employ new models of the spectral evolution of galaxies, which include a physically consistent treatment of the production of starlight and its transfer through the interstellar medium (ISM) in galaxies (Charlot & Fall 2000; Charlot & Longhetti 2001; Bruzual & Charlot 2003). In addition, the modeling accounts for the stochastic nature of SF when interpreting galaxy spectra by using large Monte Carlo libraries of different SF histories to estimate physical parameters such as stellar mass, age, and SF rates in a statistical fashion.

In this Letter, we use a similar approach to interpret the combined ultraviolet (UV) and optical colors of 6472 SDSS galaxies observed by the Galaxy Evolution Explorer (GALEX) (Martin et al. 2005). We show that the addition of UV information to the optical spectral energy distributions (SEDs) of galaxies leads to significant improvements in the estimates of the star formation rates (SFRs), starburst histories, and dust attenuations.

2. DATA AND SAMPLE

2.1. GALEX and SDSS Data

We consider galaxies with combined GALEX and SDSS photometry, for which spectroscopic redshifts are available from the SDSS. GALEX images the sky at far-UV (FUV; 1530 Å) and near-UV (NUV; 2310 Å) bands in two modes: All-sky Imaging Survey [AIS, m_{lim}(AB) \approx 20.4] and Medium Imaging Survey [MIS, m_{lim}(AB) \approx 22.7]. Each circular field covers 1.1 deg^2 Here we use the internal release of the catalog (IR0.2) that consists of 649 AIS and 94 MIS fields, of which 117 and 91 overlap (at least in part) with the SDSS Data Release One (DR1, Abazajian et al. 2003). We use FUV and NUV fluxes and errors derived in elliptical apertures. For GALEX sources with counterparts in the SDSS DR1 spectroscopic sample we extract SDSS ugriz model colors normalized to the Petrosian r magnitude, 90% and 50% Petrosian i-band radii, and the


The SDSS between 0.05 and 0.15 (the number of SDSS galaxies with criteria that remove solved SDSS objects, we additionally impose astrometric criteria to match or matching an unresolved object with re-

We characterize the PDF using the median and the 2.3%–97.7% range for Gaussian distributions), weight [∝ exp (−χ²/2)] to be assigned to the physical parameters of that model when building the probability distributions of the parameters of the given galaxy. The probability density function (PDF) of a given physical parameter is thus obtained from the distribution of the weights of all models in the library. We characterize the PDF using the median and the 2.3%–97.7% range (equivalent to ± 2σ range for Gaussian distributions), and also record the χ² of the best-fitting model. We perform this analysis for all galaxies in our sample. The distribution of χ²-values of the best-fitting models is generally very good, implying that our libraries do reproduce the observed SEDs. However, there is a tail of large χ²-values—usually identifiable as objects with suspect SDSS magnitudes, or as “shredded” objects. We remove ~300 galaxies with the poorest fits. In the end, we obtain estimates of physical parameters for 6472 galaxies.

3.3. Parameters and Their Errors

We estimate physical parameters in two ways: using the GALEX FUV and NUV fluxes combined with the SDSS ugriz fluxes, and using only the SDSS fluxes. This allows us to quantify the effect of adding ultraviolet constraints.
Table 1 summarizes our results. For each physical parameter, we list the sample-averaged parameter value \((\langle G + S \rangle)\) derived using \(GALEX\) + SDSS constraints, “1 \(\sigma\)” estimate of the average parameter error with \((G + S)\) and without \((S)\) including the \(GALEX\) constraints, and the increase in accuracy (gain) achieved with \(GALEX\). We also investigate the effect of changing the fraction (from 50\% to 10\%) of galaxies in the model libraries that had bursts over the past 2 Gyr. In Table 1 we report the resulting rms change in parameter value. It is usually much smaller than the “fitting” error, except for the time \(t_{\text{burst}}\) since the last burst of SF.

The physical parameters for which the estimates are most significantly improved with \(GALEX\) are the 100 Myr– and 1 Gyr–averaged SF rates, \([\text{SFR}\, \text{(100 Myr)}]\) and \([\text{SFR}\, \text{(1 Gyr)}]\), FUV and NUV dust attenuations \((A_{\text{FUV}}\) and \(A_{\text{NUV}}\)), and estimates of the fraction of a galaxy’s stellar mass formed in bursts \([F_{\text{burst}}\, \text{(100 Myr)}]\) and \([F_{\text{burst}}\, \text{(1 Gyr)}]\) over the last 0.1 and 1 Gyr (although it is sensitive to the assumed frequency of bursts in the model libraries).

4. ANALYSIS OF PHYSICAL PROPERTIES, STAR FORMATION, AND STARBURST HISTORIES

In Figure 1 we compare the stellar masses derived from our analysis of \(GALEX\) + SDSS colors with those derived by Kauffmann et al. (2003a). These authors used the strengths of the H\(\delta_A\) absorption-line index and 4000 Å break in the SDSS spectra (that trace the recent and past-averaged SF histories) to improve the constraints on the stellar mass-to-light ratios relative to estimates based on a single optical color. The scatter in the difference between the two types of mass estimates in Figure 1 (0.11 dex without 3 \(\sigma\) outliers) is very well matched by the uncertainties in the two studies (0.08 dex). Kauffmann et al. (2003a) also compute the fraction of a galaxy’s stellar mass formed in bursts over the last 2 Gyr. In our study, bursts over 2 Gyr are poorly constrained. This is because the UV light is less sensitive to stars older than 1 Gyr than the H\(\delta_A\) index. We have checked that galaxies for which we find \(F_{\text{burst}}\, (1 \text{ Gyr}) > 0.05\) have 4000 Å breaks and H\(\delta_A\) strengths typical of galaxies \(r < 0.05\). We present our main results in Figure 2, where we show the dependence of selected physical parameters on three fundamental galaxy properties: stellar mass, galaxy type, and color. We use the concentration parameter \(R_90/R_{50}\) as a proxy for galaxy type. Values of \(R_90/R_{50}\) larger than 2.5 correspond mostly to early-type galaxies, but late-type galaxies can also have large (Fukugita et al. 2004). We choose the \(R_90/R_{50}\) color as it provides a broad baseline and is not subject to large \(k\)-corrections. Objects are color coded to indicate whether an exponential profile (blue) or a de Vaucouleurs \(R^{1/4}\) profile (red) has higher probability. This serves as an additional rough indicator of galaxy type.

The first row of panels in Figure 2 presents the derived stellar metallicities. It was recently demonstrated that star-forming galaxies in SDSS exhibit a tight metallicity (of ISM) versus mass correlation (Tremonti et al. 2004). Although metallicity is not strongly constrained using our method (see Table 1), we do find that low-mass galaxies do not reach metallicities as high as high-mass galaxies. (Note that galaxies with \(M_r < 10^{10} M_\odot\) are preferentially disk galaxies, and mostly have \(NUV - r < 4\).) Massive galaxies span a wide range in \(Z\), with blue and red dots occupying the same space.

The second row of panels shows that low-mass galaxies on...
average suffer less attenuation than massive ones, implying that the dust content is smaller, but the range of attenuation in more massive galaxies is larger. We also find that the dust attenuation in late-type galaxies increases as their NUV $- r$ colors become redder, but early-type galaxies behave in the opposite fashion. This probably indicates that the reddest early-type galaxies have little gas, ongoing SF, and dust.

Next we examine the total current SFR (averaged over the last 100 Myr). We find that GALEX is sensitive to very low SF levels, $\sim 10^{-7} M_\odot$ yr$^{-1}$. Not surprisingly, galaxies with the lowest SFRs are primarily of early type. However, there is an interesting concentration of red dots at log SFR $\approx 0.5$. This “population” has lower concentration index and bluer NUV $- r$ color than low-SF early-type galaxies. Inspection of the images of a subset of these galaxies with high metallicities reveals that about half of them are spirals (often disrupted), while most others show (low surface brightness) disks. Some 10% appear to be true ellipticals. This emphasizes the crudeness of classification based on profile fitting. Finally, we note that we compared our SFRs with those derived from aperture-corrected nebular emission (Brinchmann et al. 2004) and found excellent overall agreement. A more detailed comparison of SF metrics will be presented elsewhere.

The last row shows the ratio of current (last 100 Myr) to past-averaged SF (the “b-parameter”). Galaxies with constant SFR will have log $b = 0$, while those undergoing a burst can have log $b > 0$. We find that $b$ is close to unity for low-mass galaxies but extends to 0.1 for massive, late-type galaxies, in agreement with the results of Brinchmann et al. (2004). Early types reach values as low as $b \approx 3 \times 10^{-4}$. The tight correlation between $b$ and NUV $- r$ color is most remarkable. It implies that the SF history of a galaxy can be constrained on the basis of the NUV $- r$ color alone.

We have also examined the relation between SFR and FUV attenuation for the galaxies in our sample. We find that increasing SFRs are always associated with larger attenuations. At a fixed attenuation, however, early-type galaxies can have SFRs several orders of magnitude smaller than late-type galaxies. This suggests a different dependence between dust content and SF in the two types of galaxies. Buat et al. (2005) also find that the dust attenuation increases with the amount of recent SF as estimated by the dust-corrected NUV flux.

One might worry that because our sample has UV selection, the results shown in Figure 2 may not apply to the galaxy population as a whole. We have analyzed the relations between the same galaxy properties as in Figure 2 for the MIS fields, where the UV coverage of galaxies in the SDSS spectroscopic sample is substantially more complete. We found exactly the same relations between SFR, $b$, and $A_{\text{FUV}}$, mass, concentration, and color. The most notable difference is that the MIS data (by virtue of going deeper) contain a larger fraction of massive, concentrated red galaxies. Therefore, while the above results are useful for identifying various trends, they cannot be used to study the relative proportions of galaxies with different properties.

Finally, we perform a time-resolved analysis of starbursts. We select galaxies that have experienced starburst in which more than 5% of stellar mass ($F_{\text{burst}} \geq 0.05$) was formed over the last 100 Myr and 1 Gyr. Figure 3 gives the fraction of galaxies of a given mass that have undergone a recent starburst. The dashed histogram corresponds to bursts within the last 100 Myr. For log $M_*$ < 9, the fraction is $\sim 10\%$, but it declines to zero for the most massive galaxies. Over the last 1 Gyr (solid histogram) some 20% of low-mass galaxies have experienced bursts. This fraction falls to 5% for larger masses. Qualitatively consistent results are obtained if we restrict the analysis to the MIS fields. Similar results were obtained by Kauffmann et al. (2003b), who analyzed starbursts over a 2 Gyr timescale.

In this preliminary study of SF history using the UV photometry from GALEX, we demonstrate the promise and point to possible limitations of this data set when interpreted with galaxy models. As we gather more data we should be able to better explore the trends suggested here, and to get better statistics on low-mass galaxies.

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FIG. 3.—Fraction of galaxies of a given mass with starbursts. Histograms correspond to fraction of galaxies with bursts (that produced more than 5% of stellar mass) having occurred in the last 100 Myr (dashed line) and 1 Gyr (solid line). The fraction of galaxies with recent bursts declines sharply with galaxy mass.