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


Received 2004 May 10; accepted 2004 Jul 29

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 SDSS DR1 main spectroscopic sample. Parameters are estimated in a statistical way by comparing each observed broad-band 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 are sensitive to SFRs as low as \(10^{-10} M_\odot \text{yr}^{-1}\), 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 \((b-\text{parameter})\) 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 \(\sim 10^8 M_\odot\) to ~5% for \(\sim 10^{11} M_\odot\) galaxies.

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

1. INTRODUCTION

Modern large-scale galaxy surveys are allowing new constraints to be placed 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 \(10^5\) nearby galaxies (e.g., Kauffmann et al. 2003a; 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. 2004). We show that the addition of UV information to the optical 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, \(m_{lim}(\text{AB}) \approx 20.4\)) and Medium-deep Imaging Survey (MIS, \(m_{lim}(\text{AB}) \approx 22.7\)). Each circular field covers 1.1 sq. deg. 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 likelihoods of exponential and
We construct our sample from GALEX objects matched to SDSS DR1 objects in a 6′ radius (Seibert et al. 2003). We then restrict the sample to objects spectrally classified as galaxies and with redshifts $0.005 < z < 0.25$. To avoid mismatches or matching an unresolved GALEX object with resolved SDSS objects, we additionally impose astrometric criteria which remove $\approx 10\%$ of the galaxies, leaving 6826. About 70% of the remaining galaxies have redshifts in a narrow range between 0.05 and 0.15 (the number of SDSS galaxies with spectra drops steeply when $z > 0.1$). GALEX M1 and AIS recover on average 80% and 50% of the SDSS main galaxy spectroscopic sample ($r_{\text{lim}} < 17.8$). MIS galaxies constitute 60% of our sample. The addition of UV selection leads to incompleteness for galaxies redder than $u−r \approx 3.0$ in the MIS and $u−r > 2.5$ in the AIS. However, brighter red galaxies are still present in our sample.

3. MODEL GALAXY PARAMETERS

3.1. Libraries of galaxy models

We use the Bruzual & Charlot (2003) population synthesis code to generate libraries of stochastic realizations of model SF histories at five redshifts equally spaced between 0.05 and 0.25. Each library contains $\sim 10^9$ models. For simplicity, we follow Kauffmann et al. (2003) and parameterize each SF history in terms of two components: an underlying continuous model with an exponentially declining SF law (SFR$(t) \propto \exp[-\gamma t]$) and random bursts superimposed on this continuous model. Attenuation by dust is described by means of two main parameters (see Charlot & Fall 2000): the effective V-band absorption optical depth $\tau_V$ affecting stars younger than 10 Myr (that arises from giant molecular clouds and the diffuse ISM) and the fraction $\mu$ of it contributed by the diffuse ISM, that also affects older stars. Based on previous analyses of SDSS galaxies (Kaufmann et al. 2003a, Brinchmann et al. 2003), we take $\gamma_V$ to be distributed from 0 to 6 with a broad peak around 1 and $\mu$ to be distributed from 0.1 to 1 with a broad peak around 0.3. Our model galaxies have metallicities uniformly distributed between 0.1 and 2 $Z_\odot$.

3.2. Deriving physical parameters

We derive statistical estimates of various physical parameters by comparing the observed SED of each galaxy in the sample to the model SEDs as follows. First, we convert SDSS magnitudes into fluxes, correcting for the offsets between the SDSS- and AB-magnitude zeropoints (Abazajian et al. 2004) and applying small zeropoint offsets to GALEX fluxes. To SDSS flux errors we add calibration errors in quadrature. After accounting for Galactic reddening, we compare the SED of the observed galaxy to all SEDs in the closest-redshift model library. The $\chi^2$ goodness of fit of each model determines the weight ($\propto \exp[-\chi^2/2]$) 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 percentile range (equivalent to $\pm 2\sigma$ range for Gaussian distributions), and also record the $\chi^2$ of the best-fitting model. We perform this analysis for all galaxies in our sample. The distribution of $\chi^2$ 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 $\chi^2$ values—usually identifiable as objects with suspect SDSS magnitudes, or as “shredded” objects. We remove $\sim 300$ galaxies with 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.

The burst probability is set so that 50% of the galaxies in the library have experienced a burst in the past 2 Gyr.

\begin{table}[h]
\centering
\begin{tabular}{lcccc}
\hline
Parameter name & $\langle G+S \rangle$ & RMS $\Delta (G+S)^a$ & $\langle \sigma(G+S) \rangle$ & $\langle \sigma(S) \rangle$ & Gain$^b$
\hline
$t_{gal}$ & 6.50 & 0.53 & 1.91 & 2.16 & 12%
$\tau$ & 0.40 & 0.06 & 0.21 & 0.22 & 7%
$Z/Z_\odot$ & 1.00 & 0.14 & 0.36 & 0.42 & 12%
$\gamma_V$ & 1.24 & 0.17 & 0.60 & 0.86 & 29%
$\mu$ & 0.36 & 0.03 & 0.14 & 0.15 & 6%
$A_{FUV}$ & 2.03 & 0.23 & 0.62 & 1.05 & 41%
$A_{NUV}$ & 1.46 & 0.18 & 0.46 & 0.78 & 41%
$\log M_*$ & 10.42 & 0.02 & 0.08 & 0.09 & 11%
$\log SFR(100 \text{ Myr})$ & 0.00 & 0.07 & 0.27 & 0.54 & 49%
$\log SFR(1 \text{ Gyr})$ & 0.18 & 0.12 & 0.30 & 0.55 & 45%
$\log SFR(10 \text{ Gyr})$ & 0.00 & 0.06 & 0.01 & 0.01 & 39% (1 Gyr)
$\log SFR(100 \text{ Myr})$ & 0.02 & 0.08 & 0.04 & 0.06 & 39%
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1}
\caption{Comparison of galaxy stellar masses derived in Kauffmann et al. (2003a) and in this Letter. The difference $\Delta(\log M_*)$ is in the sense $\log M_\text{this Letter} - \log M_\text{Kauffmann et al. (2003a)}.}$
\end{figure}
Table 1 summarizes our results. For each physical parameter, we list the sample-averaged parameter value \((\langle G+S \rangle)\) derived using \textit{GALEX} + SDSS constraints, “1σ” estimate of the average parameter error with \((G+S)\) and without \((S)\) including the \textit{GALEX} constraints, and the increase in accuracy (gain) achieved with \textit{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 \textit{GALEX} are the 100 Myr- and 1 Gyr-averaged SF rates, \((\text{SFR}(100 \text{ Myr})\) and \((\text{SFR}(1 \text{ Gyr})\), 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 \((F_{\text{burst}}(100 \text{ Myr})\) and \((F_{\text{burst}}(1 \text{ Gyr})\)) 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 \textit{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 (0.11 dex without 3σ 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 for which Kauffmann et al. (2003a) find \(F_{\text{burst}}(2 \text{ Gyr}) > 0.05\).

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 \(R_{90}/R_{50}\) (Fukugita et al. 2004). We choose the \(NUV-r\) 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) vs. 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
Early-type galaxies reach values as low as $NUV - r < 4.3$; 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, $\sim 10^{-3} M_\odot$ yr$^{-1}$. Surprisingly, galaxies with the lowest SFRs are primarily of early type. However, there is an interesting concentration of red dots at log SFR $\sim 0.5$. 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-types 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. 2004 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 SF, $b$, $A_{FUV}$ and 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 having 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 dataset 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.

We thank Sukyoung Yi for comments. SS thanks Andrew Gould. SC thanks the Alexander von Humboldt Foundation. GALEX is a NASA Small Explorer, launched in April 2003. We gratefully acknowledge NASA’s support for construction, operation, and science analysis for the GALEX mission, developed in cooperation with the CNES of France and the Korean Ministry of Science and Technology. Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the NASA, the NSF, DoE, Monbukagakusho, and the Max Planck Society.

REFERENCES