EVOLUTION OF THE Hα LUMINOSITY FUNCTION

Eduard Westra¹, Margaret J. Geller¹, Michael J. Kurtz¹, Daniel G. Fabricant¹, and Ian Dell’Antonio²

¹ Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA; ewestra@cfa.harvard.edu
² Brown University, Department of Physics, Box 1843, Providence, RI 02912, USA

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ABSTRACT

The Smithsonian Hectospec Lensing Survey (SHELS) is a window on the star formation history over the last 4 Gyr. SHELS is a spectroscopically complete survey for $R_{\text{tot}} < 20.3$ over $4^{\circ}$. We use the 10k spectra to select a sample of pure star-forming galaxies based on their Hα emission line. We use the spectroscopy to determine extinction corrections for individual galaxies and to remove active galaxies in order to reduce systematic uncertainties. We use the large volume of SHELS with the depth of a narrowband survey for Hα galaxies at $z \sim 0.24$ to make a combined determination of the Hα luminosity function at $z \sim 0.24$. The large area covered by SHELS yields a survey volume big enough to determine the bright end of the Hα luminosity function from redshift 0.100 to 0.377 for an assumed fixed faint-end slope $\alpha = -1.20$. The bright end evolves: the characteristic luminosity $L^{\star}$ increases by 0.84 dex over this redshift range. Similarly, the star formation density increases by 0.11 dex. The fraction of galaxies with a close neighbor increases by a factor of 2–5 for $L_{\text{Hα}} > L^{\star}$ in each of the redshift bins. We conclude that triggered star formation is an important influence for star-forming galaxies with Hα emission.

Key words: galaxies: evolution – galaxies: interactions – galaxies: luminosity function, mass function – galaxies: starburst

Online-only material: color figures

1. INTRODUCTION

Determining the star formation history of the universe is a crucial part of understanding the formation and evolution of galaxies. Exploration of the global star formation history has two components: (1) measurement of the star formation density over time and (2) understanding the physical processes that drive star formation. Here, we use a large, moderate-depth spectroscopic survey to address both issues: (1) we determine the star formation density over the last 4 Gyr using the Hα emission line as star formation indicator and (2) we investigate the possible influence of galaxy interactions on the Hα luminosity function.

There is abundant observational evidence for an order of magnitude increase in the star formation density since redshift $z \sim 1–2$ (Lilly et al. 1996; Madau et al. 1996; the compilations of Hopkins 2004; Hopkins & Beacom 2006). Major mergers, tidal interactions, gas removal from conversion into stars, and/or ram pressure stripping may explain the decrease in the star formation. The challenge is deciding which of these processes are important in the quenching of star formation (Bell et al. 2005).

The decline in star formation density coincides with a rapid decrease in the characteristic luminosity of galaxies ($L^{\star}$) in the rest-frame $U$ band (e.g., Ilbert et al. 2005; Prescott et al. 2009). A decrease in the number of merging systems can explain the decrease of the characteristic luminosity $L^{\star}$ (Le Fèvre et al. 2000). Sobral et al. (2009) find a strong morphology–Hα luminosity relation for mergers and non-mergers. The characteristic luminosity $L^{\star}$ defines a critical switch-over luminosity between the mergers and non-mergers; the mergers are more luminous.

Studies of close pairs show that enhancement in the star formation rate (SFR) is largest for galaxies in major pairs ($|\Delta m| \lesssim 0.7$–2; Woods et al. 2006; Woods & Geller 2007; Ellison et al. 2008) and that the average SFR in a galaxy increases with decreasing projected separation (Li et al. 2008). Simulations of interacting and merging galaxies reveal that the interactions can trigger short powerful bursts of star formation by forcing substantial fractions of the gas into the central regions (Mihos & Hernquist 1996).

Systematic effects dominate the comparison of SFRs determined from different star formation indicators like the rest-frame ultraviolet (UV) and Hα. Hence, to study the variation of the star formation density with time, the use of a single star formation indicator is best. The rest-frame UV spectrum of a galaxy directly measures the population of newborn stars (e.g., Lilly et al. 1996; Treyer et al. 1998). However, the rest-frame UV is strongly attenuated (e.g., Cardelli et al. 1989; Calzetti et al. 2000) at $z > 1$. The most direct optical indicator is the Hα emission line emitted by gas surrounding the embedded star-forming region (e.g., Kennicutt 1998). The Hα line is also affected by attenuation—albeit less than the UV—which can be corrected using spectroscopy.

Many surveys use narrowband filters (Thompson et al. 1996; Moorwood et al. 2000; Jones & Bland-Hawthorn 2001; Fujita et al. 2003; Hippelein et al. 2003; Ly et al. 2007; Pascual et al. 2007; Dale et al. 2008; Geach et al. 2008; Morioka et al. 2008; Shioya et al. 2008; Villar et al. 2008; Westra & Jones 2008; Sobral et al. 2009) to determine the Hα luminosity function parameters over a range of redshifts. Despite the depth of the narrowband surveys, measurements of individual luminosity function parameters and the star formation density are not well constrained.

Narrowband surveys lack spectroscopy for the faint Hα emitting galaxies. Thus, general assumptions about stellar absorption, extinction corrections, contributions by active galactic nuclei (AGNs), or interloper contamination need to be made for the sample as a whole rather than for each galaxy. These issues may lead to systematic uncertainties. Massarotti et al. (2001) show that applying an average extinction correction introduces a systematic underestimation of the extinction-corrected star formation density. A spectroscopic survey does not suffer these limitations, although it is usually limited in its depth.
Several spectroscopic Hα surveys exist (e.g., Gallego et al. 1995; Tresse & Maddox 1998; Sullivan et al. 2000; Tresse et al. 2002; Pérez-González et al. 2003; Shim et al. 2009). Both Gallego et al. and Pérez-González et al. use the Universidad Complutense de Madrid (UCM) survey. This survey covers an extremely wide area on the sky (472°2). However, it is limited to a very low redshift ($z_{\text{max}} \sim 0.045$). For their Hα survey, Sullivan et al. (2000) use galaxies selected from UV imaging in a 2.2" field. The other surveys have an area $\lesssim 0.25\,\text{deg}^2$. Thus, most surveys are too limited in volume to overcome cosmic variance.

The Smithsonian Hectospec Lensing Survey (SHELS) is a spectroscopic survey covering 4° on the sky to a limiting R-band magnitude $R_{\text{tot}} = 20.3$ (Geller et al. 2005). We use SHELS to obtain a consistent determination of the star formation history over the last 4 Gyr based on the Hα emission line over a relatively large area and redshift range.

The spectroscopy enables us to reduce systematic uncertainties by allowing an individual galaxy extinction correction. We can also remove individual AGN rather than applying a global correction factor for contamination by AGNs as is done in narrowband surveys. We use the large survey area to determine the characteristic luminosity $L^*$ of the Hα luminosity function and associated systematic uncertainties.

We discuss the SHELS spectroscopic data in Section 2. In Section 3, we introduce our Hα sample selection. We combine our R band selected Hα sample with the narrowband Hα survey of Shioya et al. (2008) in Section 4 to obtain a jointly determined Hα luminosity function at $z \sim 0.24$. Sections 5 and 6 discuss the derivation and evolution of the luminosity function and star formation density, respectively, over the past 4 Gyr. We include an investigation of the influence of our selection criteria on the derivation of the luminosity function parameters. In Section 7, we examine the stellar age of the star-forming galaxies and the influence of galaxy–galaxy interactions on these galaxies. We summarize our results in Section 8.

Throughout this paper, we assume a flat universe with $H_0 = 71 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$. All quoted magnitudes are on the AB system and luminosities are in erg s$^{-1}$.

### 2. SHELS OBSERVATIONS

We constructed the SHELS galaxy catalog from the R-band source list for the F2 field of the Deep Lens Survey (Wittman et al. 2002, 2006). The DLS is an NOAO key program covering 20°2 in five separate fields; the 4.2°2 F2 field is centered at $\alpha = 09^h19^m32.4^s$ and $\delta = +30^\circ00'00''$. We exclude regions around bright stars (5% of the total survey) resulting in an effective area of 4.0°2. We use surface brightness and magnitude to separate stars from galaxies. This selection removes some AGNs.

Photometric observations of F2 were made with the Mosaic I imager (Muller et al. 1998) on the KPNO Mayall 4 m telescope between 1999 November and 2004 November. The R-band exposures, all taken in seeing $< 0.9$ FWHM, are the basis for the SHELS survey. The effective exposure time is about 14,500 s and the 1σ surface brightness limit in $R$ is 28.7 mag per square arcsecond. Wittman et al. (2006) describe the reduction pipeline.

We acquired spectra for the galaxies with the Hectospec fiber-fed spectrograph (Fabricant et al. 1998, 2005) on the MMT from 2004 April 13 to 2007 April 20. The spectrograph is fed by 300 fibers that can be positioned over a 1° field. Roughly 30 fibers per exposure are used to determine the sky. The Hectospec observation planning software (Roll et al. 1998) enables efficient acquisition of a magnitude limited sample.

The SHELS spectra cover the wavelength range $\lambda = 3500$–10000 Å with a resolution of ~6 Å. Exposure times ranged from 0.75 hr to 2 hr for the lowest surface brightness objects in the survey. We reduced the data with the standard Hectospec pipeline (Mink et al. 2007) and derived redshifts with RVSAO (Kurtz & Mink 1998) with templates constructed for this purpose (Fabricant et al. 2005). We have 1468 objects that have been observed twice. These repeat observations imply a mean internal error of 56 km s$^{-1}$ for absorption-line objects and 21 km s$^{-1}$ for emission-line objects (see also Fabricant et al. 2005).

Fabricant et al. (2008) describe the technique we use for photometric calibration of the Hectospec spectra based on the particularly stable instrument response. For galaxies in common between SHELS and SDSS, the normalized Hα line fluxes agree well in spite of the difference in fiber diameters for the Hectospec (1.5") and the SDSS (3"). For high signal-to-noise SHELS spectra, the typical uncertainties in emission line fluxes are 18%.

SHELS includes 9825 galaxies to the limiting apparent magnitude. The overall completeness of the redshift survey to a total R-band magnitude of $R_{\text{tot}} \lesssim 20.3$ is 97.7%, i.e., 9595 galaxies have a redshift measured; the differential completeness at the limiting magnitude is 94.6%. The 230 objects without redshifts are low surface and/or faint objects, or objects near the survey corners and edges. M. J. Kurtz et al. (2010, in preparation) includes a detailed description of the full redshift survey.

The SHELS survey also includes 1852 galaxies with 20.3 < $R$ < 20.6, for which we have measured a redshift; the total sample of galaxies with 20.3 < $R$ < 20.6 is 3590, i.e., the survey is 52% complete in this magnitude interval. The completeness is patchy across the field.

The F2 field contains an atypical underdense region at the lowest redshifts because the DLS fields are selected against nearby clusters at $z < 0.1$. We show the redshift distribution of our Hα galaxies in Figure 1.

#### 2.1. The R-band k+c-corrections

To calculate the absolute R-band magnitude $M_R$, we determine the appropriate k+c-corrections. The k+c-correction converts the observed absolute magnitude to the rest frame of the galaxy, correcting for redshift and evolution. We use the k+c-corrections for nine types of galaxies: bright cluster (BCG), elliptical (E), S0, Sa, Sb, Sbc, Sc, Sd and irregular (Irr) galaxies determined by J. Annis (2000, private communication). We use the corrections for the SDSS r'-filter as a function of redshift and $(g'-i')$ color because the SDSS r'-filter is similar to the R-filter used for the DLS. We obtain $(g'-i')$ by cross-matching our catalog with SDSS DR6 (Adelman-McCarthy et al. 2008). For those galaxies not found in SDSS DR6 (these galaxies are either unresolved or below the surface brightness limit in SDSS) we convert the $(V-R)$ from 61 galaxies in the DLS to $(g'-i')$. For 42 galaxies, we cannot determine or derive $(g'-i')$ due to the proximity of another object; we assume that these are Sa galaxies. We interpolate the models in redshift to obtain the k+c-corrections for each galaxy type determined by its $(g'-i')$ and redshift.

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3 The total magnitude is the SExtractor (Bertin & Arnouts 1996) MAG_AUTO as opposed to an aperture magnitude.

4 The table with the corrections for the SDSS r'-filter set as function of galaxy type and redshift can be obtained from http://home.fnal.gov/~annis/astrophys/kcorr/kcorr.html.
3. Hα SAMPLE SELECTION

We use SHELS to construct Hα luminosity functions over the redshift range 0.010 < z < 0.377 (Table 1). Here, we describe the determination of our final emission-line luminosities and the discrimination between pure star-forming galaxies and AGNs.

### 3.1. Emission-line Measurements

The emission-line flux emanating from star-forming regions is affected by the absorption-line spectrum from the underlying stellar population. The absorption mostly affects the measurements of the hydrogen Balmer lines. To measure the emission-line flux we thus remove the contribution of the stellar population.

We use the Tremonti et al. (2004) continuum subtraction method to correct for the stellar absorption rather than applying a constant, global correction (e.g., Hopkins et al. 2003). The Tremonti et al. method removes the stellar continuum by fitting a linear combination of template spectra resampled to the correct velocity dispersion. The method also accounts for redshift and reddening. The template spectra are based on single stellar population models generated by the population synthesis code of Bruzual & Charlot (2003). We use models with 10 different ages (0.005, 0.025, 0.1, 0.3, 0.6, 0.9, 1.4, 2.5, 5, and 10 Gyr) at solar metallicity.

We determine the emission-line fluxes from the continuum-subtracted spectra by integrating the line flux within a top-hat filter centered on the emission line. We remove any local over- or under-subtraction of the continuum by subtracting the mean of the flux-density at both sides of the filter. Next, we determine the continuum level by taking the mean of the flux-density at wavelengths bluer and redder than the emission line on the best-fit continuum model. Finally, we determine the absorption contribution of the underlying stellar population using the same top-hat filter but on the best-fit model; we remove the flux contributed by the continuum.

The Hectospec fibers have a fixed diameter of 1''5. At all redshifts, where Hα is observable (and in particular at the lowest redshifts) the fiber does not cover the entire galaxy. Hence, we use an aperture correction

\[ A = 10^{-0.4(m_{\text{total}} - m_{\text{fiber}})} \]

(1)

to correct for the fiber-covering fraction. Figure 2 shows the fraction of light, 1/A, contained in the fiber as a function of redshift.

Kewley et al. (2005) show that a spectrum measuring at least 20% of the galaxy light avoids substantial scatter between the nuclear and integrated SFR measurements. The overall majority of galaxies from SHELS have a light-fraction 1/A > 20% (Figure 2).

Fabricant et al. (2008) compared the Hα and [O III] emission-line fluxes from SHELS with SDSS DR6 after making an aperture correction. They found excellent agreement between

![Figure 1. Redshift cone diagram for the galaxies in the final sample: R_{tot} \leq 20.3, S/N_{Hα} > 5, and f_{Hα} \geq 10^{-15.5} \text{ erg s}^{-1} \text{ cm}^{-2}. AGNs have not been removed from this sample. The large-scale structure is apparent with extended low-density regions and well-populated narrow structures.](image1)

| Criterion | 0.01 \leq z < 0.10 | 0.10 \leq z < 0.20 | 0.20 \leq z < 0.30 | 0.30 \leq z < 0.38 | Total |
|-----------|-----------------|-----------------|-----------------|-----------------|-------|
| (1) R_{tot} \leq 20.3 | 461 | 1949 | 2746 | 2114 | 7270 |
| (2) S/N_{Hα} > 5 | 420 | 1640 | 1857 | 1275 | 5192 |
| (3) log f_{Hα} > -15.5 | 369 | 1441 | 1702 | 1186 | 4698 |
| (4) Pure star forming | 322 | 1127 | 1268 | 848 | 3565 |

**Table 1** Number of Galaxies Satisfying Each Selection Criterion

**Note.** Successive lines are a subset of the line above. We apply the selection criteria sequentially in the order of the Table.
the two surveys, even though the fibers of the SDSS spectrograph are 3′ in diameter. Moreover, most of the SDSS galaxies are at low redshift (\(z \lesssim 0.14\)) where we have the largest fraction of galaxies with a light-fraction less than 20%.

There is no dependence of final H\(\alpha\) luminosity on the light-fraction. We are thus confident that the use of these aperture ratios does not affect the final results even when the covering fraction is small.

### 3.2. Extinction Correction

The light from star-forming regions in a galaxy is often heavily attenuated. To determine the intrinsic SFR of a galaxy we must remove the effects of attenuation.

We calculate the attenuation by comparing the observed value of the Balmer decrement (corrected for stellar absorption) with the theoretical value (\(f_{\text{obs}}/f_{\text{tot}} = 2.87\) for \(T = 10^4\) K and case B recombination; Table 2 of Calzetti 2001). The intrinsic flux is \(f_{\text{intrinsic}}(\lambda) = f_{\text{obs}}(\lambda)10^{\Delta A\lambda}\), where \(A\lambda\) is the wavelength-dependent extinction. \(A\lambda\) is

\[
A\lambda = k(\lambda)E(B-V)_{\text{gas}} = k(\lambda)\frac{2.5 \log R_{\alpha\beta}}{k(H\beta) - k(H\alpha)},
\]

where \(R_{\alpha\beta}\) is the ratio of the attenuated-to-intrinsic Balmer line ratios, \(k(H\beta) - k(H\alpha)\) is the differential extinction between the wavelengths of H\(\beta\) and H\(\alpha\), and \(k(\lambda)\) is the extinction at wavelength \(\lambda\). We apply the Calzetti et al. (2000) extinction law, which has \(k(V) = 4.05\), \(k(H\alpha) = 3.325\), and \(k(H\beta) = 4.596\).

Figure 3 shows the attenuation as a function of observed H\(\alpha\) luminosity. The black line indicates the least-absolute-deviates fitted to the gray points. We indicate the fraction of galaxies with more than 20% of the light contained in the fiber (horizontal dashed line) for each redshift bin (vertical dashed lines) where \(A_{\text{H\alpha}} > 0\) (solid horizontal line) and a commonly assumed value of \(A_{\text{H\alpha}} = 1\), dashed horizontal line; e.g., Tresse & Maddox 1998; Fujita et al. 2003; Ly et al. 2007; Sobral et al. 2009

### 3.3. Sample Definition

Figure 4 shows the H\(\alpha\) luminosity as a function of redshift. Below \(f_{\text{tot}} = 10^{-15.5}\) erg s\(^{-1}\) cm\(^{-2}\), the number of galaxies decreases rapidly. We impose a constant H\(\alpha\) flux limit \(f_{\text{H\alpha}} \geq 10^{-15.5}\) erg s\(^{-1}\) cm\(^{-2}\) on the sample (after corrections for stellar absorption and attenuation) because we are only complete to this flux. We apply this criterion in addition to the magnitude limit \(R_{\text{tot}} \leq 20.3\) and the S/N\(_{\text{H\alpha}} \geq 3\) requirement.

### 3.4. AGN Classification

The presence of an active nucleus in a galaxy contributes to the (apparent) star formation in the galaxy. For example, Pascual et al. (2001) find that approximately 15% of the luminosity density of the UCM survey (Gallego et al. 1995) results from galaxies identified as AGNs. Westra & Jones (2008) find a 5% contribution for their survey.

We use the demarcations of pure star formation from Kauffmann et al. (2003) and of extreme starburst from Kewley et al. (2001) to identify galaxies as pure star forming, AGN, or

Figure 4. H\(\alpha\) luminosity (corrected for observed H\(\alpha\) luminosity. The solid line indicates the additional selection criterion \(f_{\text{H\alpha}} \geq 10^{-15.5}\) erg s\(^{-1}\) cm\(^{-2}\). Vertical dashed lines show the edges of the redshift bins used to construct the SHELs H\(\alpha\) luminosity functions.
However, we cannot draw any conclusions about the evolution of the AGN fraction as a function of redshift. We removed stellar objects from the initial sample and thus may have inadvertently removed AGNs particular at greater redshifts.

4. THE Hα LUMINOSITY FUNCTION AT REDSHIFT ~0.24

The recent advent of wide-field cameras on telescopes has aided searches for star-forming galaxies by increasing the area (and hence volume) of narrowband surveys, e.g., Fujita et al. (2003), Ly et al. (2007), Shioya et al. (2008), Westra & Jones (2008), and many more. This technique has recently been extended to the near-infrared, e.g., Sobral et al. (2009).

A narrowband survey efficiently probes the faint end of the luminosity function which is hard to explore in a spectroscopic survey. In contrast, a spectroscopic survey can cover a larger volume and sample the rare luminous galaxies at the bright end of the luminosity function.

Here, we combine the strength of a narrowband survey—the ability to go deep—with that of our broadband selected spectroscopic survey—coverage of a large volume—to determine a well-constrained luminosity function at $z \sim 0.24$. For the narrowband survey, we use the publicly available data from Shioya et al. (2008), hereafter S08 together with that of the Cosmic Evolution Survey (COSMOS, Capak et al. 2007), which formed the basis of the survey of S08. We use the spectroscopic survey of SHELS for the bright end of the luminosity function.

The S08 and SHELS surveys use different approaches (imaging versus spectroscopy). A comparison of the data allows a consistency check of the aperture corrections applied to the SHELS data.

We construct the Hα luminosity function over the redshift range of S08 ($0.233 < z < 0.251$) based on the catalog with emission-line fluxes determined in Section 3.1 (which already include corrections for underlying stellar absorption), redshifts, extinction corrections from Section 3.2, and removal of composites and AGNs (Section 3.4). Constraining SHELS to the same redshift range yields a sample of 192 SHELS galaxies at $0.233 < z < 0.251$.

4.1. Data Comparison

Figure 6 shows the Hα luminosity, Hα rest-frame equivalent width (REW), and the 3″ aperture absolute R-band magnitude from S08 (solid black circles) matched to the selection criteria of SHELS, $R_{\text{tot}} \leq 20.3$. We also show the SHELS data (open red squares) for the redshift range covered by S08 ($0.233 < z < 0.251$). To match S08, we require an observed equivalent width of Hα combined with [N II] $\lambda\lambda 6550,6585$ lines are not distinguishable from the Hα line in a spectrum with a very broad Hα line.

Inspecting each spectrum would be time consuming. Hence, we fitted the Hα and Hβ lines in the continuum-subtracted spectra in an automated way and individually inspected each candidate broad-line AGN. We fitted both lines simultaneously with the assumption that the full-width-half-maximum (FWHM) of the line profile is the same for both lines. Candidate broad-line AGNs have a peak of both Hα and Hβ $\geq 5 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ above the continuum residuals (which avoids the inclusion of noise peaks) and a FWHM of the Gaussian component of the line profile (we use a Gaussian convolved with the instrumental profile as our line profile) before convolution larger than 14 Å. From these candidates, we select the galaxies that are genuine broad-line AGNs.

The fraction of galaxies identified as AGN and/or composite over the redshift ranges 0.010–0.100, 0.100–0.200, 0.200–0.300, 0.300–0.377 for an Hα luminosity limited sample ($\log L > 41.18$; lowest Hα luminosity at $z = 0.377$) is 5.9%, 6.6%, 5.3%, and 5.2%, respectively.

The fraction of AGN is more or less constant with redshift. However, we cannot draw any conclusions about the evolution of the AGN fraction as a function of redshift. We removed stellar objects from the initial sample and thus may have inadvertently removed AGNs particular at greater redshifts.

5 The COSMOS catalog can be downloaded from http://irsa.ipac.caltech.edu/data/COSMOS/tables/cosmos_phot_20060103.tbl.gz.
to the total magnitude introduces no systematic biases and is consistent with S08.

If we constrain the data of S08 to \( f_{\text{H}\alpha} = 10^{-15.5} \text{ erg s}^{-1} \text{ cm}^{-2} \), a difference at the bright end becomes apparent (see Figure 7). There are more luminous galaxies in SHELS than in S08. This difference results from two effects: (1) SHELS probes a larger volume, and (2) the H\( \alpha \) fluxes determined from narrowband surveys can easily underestimate the true line flux. Galaxies with redshifts that place the H\( \alpha \) line in the wings of the filter underestimate the mean recovered H\( \alpha \) flux.

To examine the redshift distribution of the galaxies in S08, Figure 8 shows the redshift distribution of the 10k zCOSMOS catalog\(^6\) (Lilly et al. 2007) in combination with the filter transmission curve of the NB816 normalized to the maximum throughput.\(^7\) Any galaxy with a redshift placing it in the wings of the narrowband filter has its H\( \alpha \) flux underestimated far more than the 21% S08 use to correct their line fluxes. In the COSMOS field, the galaxies tend to be at redshifts toward the red edge of the filter. In this case, the [N\text{ii}] \( \lambda 6585 \) line (the strongest of the two [N\text{ii}] lines that straddle H\( \alpha \)) barely contributes to the flux probed by the filter. Both the underestimation of the H\( \alpha \) flux and overcorrection for [N\text{ii}] can explain the difference in the distribution of H\( \alpha \) fluxes in Figure 7.

Despite this difference, we can still use the fainter galaxies from S08 to determine the faint-end slope of the H\( \alpha \) luminosity function. The systematic underestimation of fluxes causes a shift in the luminosity function which affects the determination of the characteristic luminosity (i.e., bright end), not the faint-end slope.

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\(^6\) zCOSMOS DR2, which can be obtained from the ESO archives.

\(^7\) The filter profile is available at http://www.naoj.org/Observing/Instruments/SCam/txt/NB816.txt.
4.2. Derivation and Fit

We fitted a Schechter function (Schechter 1976) to the SHELS and S08 data. The Schechter function is

$$\phi(L)dL = \phi^*(L/L^*)^{-\alpha} \exp\left(-\frac{L}{L^*}\right) d\left(\frac{L}{L^*}\right),$$

(3)

where $\alpha$ is the slope of the faint-end part, $L^*$ is a characteristic luminosity, and $\phi^*$ is the normalization. Throughout this paper, the units for the Schechter parameters $L^*$ and $\phi^*$ are erg s$^{-1}$ and Mpc$^{-3}$, respectively. $\alpha$ is dimensionless.

To combine the two data sets, we use the non-parametric $1/V_{\text{max}}$ method (Schmidt 1968) to determine the Schechter parameters. The number density of galaxies for each luminosity bin $j$ with a width of $\Delta \log L$ is

$$\phi(L_j)d\Delta \log L = \sum_{i=1}^{N_{\text{gal}}} \frac{W(L_i)}{V_i},$$

(4)

where $W(x) = 1$ when the luminosity is enclosed by bin $j$ and $W(x) = 0$ otherwise, and $V_i$ is the volume sampled by galaxy $i$. The uncertainties in the bins are Poisson errors

$$\sigma_{\phi(L_j)}^2 = \sum_{i=1}^{N_{\text{gal}}} \frac{W(L_i)}{V_i}. $$

(5)

Figure 9 shows the luminosity function for the combined data set (thick solid line). For both surveys, we apply the selection criteria $R_{\text{tot}} \leq 20.3$, OEW$_{[\text{NII}]} \geq 12$ Å, and $0.233 < z < 0.251$.

We determine the data points using $1/V_{\text{max}}$ where the uncertainties are Poisson errors for both SHELS (solid squares) and S08 (open squares). We fitted a Schechter function with common $L^*$ and $\alpha$ to the combined SHELS and S08 data set. For this fit, we use the data with log $L_{\text{H}\alpha} \geq 41.4$ for SHELS and log $L_{\text{H}\alpha} \geq 39.6$ for S08. We recover a single value for $\alpha$ and $L^*$ of the joint fit: $\alpha = -1.41 \pm 0.03$ and log $L^* = 42.14 \pm 0.08$. For those values, the normalization for SHELS is log $\phi^*_\text{SHELS} = -3.11 \pm 0.09$ and for S08 is log $\phi^*_\text{S08} = -2.91 \pm 0.09$. We combine $\phi^*_\text{SHELS}$ and $\phi^*_\text{S08}$ using a volume-weighted average. Thus,

$$\log \phi^*_\text{comb} = \log[(1.5 \times 10^{-2.91} + 4.0 \times 10^{-3.11})/5.5] = -3.05.$$  

This method of combining is one way to account for cosmic variance. We adopt $\alpha = -1.41 \pm 0.03$, log $L^* = 42.14 \pm 0.08$, log $\phi^*_\text{comb} = -3.05 \pm 0.09$ for comparison to other surveys.

5. THE H$\alpha$ LUMINOSITY FUNCTIONS FROM SHELS

Here, we use SHELS to determine the H$\alpha$ luminosity functions as a function of redshift. We can identify H$\alpha$ in our spectra up to a redshift of $z_{\text{max}} = 0.377$. We next examine the influence of the $R$-magnitude limited survey on the derivation of the H$\alpha$ luminosity function. We limit our sample to $I_{\text{H}\alpha} \geq 10^{-15.5}$ erg s$^{-1}$ cm$^{-2}$ (see Section 3.3). Table 1 lists the number of galaxies satisfying each selection criterion. Figure 4 shows the distribution of the H$\alpha$ luminosity as a function of redshift and the redshift bins used to construct the H$\alpha$ luminosity functions.

5.1. Derivation and Fit

Here, we use the STY-method (Sandage et al. 1979), a parametric estimation method, to determine the three Schechter parameters for each redshift bin. The STY-method identifies the luminosity function parameters that maximize the probability of obtaining the observed sample. The probability $P$ is

$$P = \prod_{i=1}^{N_{\text{gal}}} \frac{\phi(L_i)}{\int_{L(z)_{\text{lim},i}}^{\infty} \phi(L)dL},$$

(6)

where $L(z)_{\text{lim},i}$ is the faintest luminosity where galaxy $i$ at redshift $z_i$ is observable. We use a truncated-Newton method to maximize the natural logarithm of $P$.

Table 2 lists the fitted parameters, and Figure 10 shows the results. We fit for $\alpha$, $L^*$, and $\phi^*$ (dashed lines). We also use a fixed $\alpha = -1.20$ (solid lines). This fixed value represents the slope over the redshift range $0.05 < z < 0.20$ for SHELS. This range has a large enough volume to sample the bright end of the luminosity function, while still having galaxies faint enough...
to determine the faint end slope. We do not consider this large redshift range in our further analysis.

Narrowband surveys apply a correction to the total luminosity density for galaxies hosting an AGN (e.g., Fujita et al. 2003; Ly et al. 2007; Shioya et al. 2008; Westra & Jones 2008). A large fraction of these surveys have little or no spectroscopy. Thus there is no way to separate AGNs from star forming galaxies. SHELS enables a direct separation (see Section 3.4). We derive the Schechter parameters for the Hα emitting galaxies with the AGNs removed (Table 2). Removal of AGNs moves \( L^* \) slightly fainter and reduces the normalization because AGNs are systematically in more luminous galaxies. Failure to account for this bias introduces a systematic offset.

We determine the final uncertainties in the Schechter parameters by constructing 1000 sets of Hα luminosities. We simulate the Hα luminosities by converting the observed absolute magnitudes into Hα luminosities using the distribution of \( L_{Hα} \) as a function of \( M_{Hα} \) for each redshift bin from Figure 11. We re-determine the Schechter parameters for each simulation using the STY-method. The 1σ spread in the re-determined parameters is the final uncertainty which includes the formal fitting uncertainty, uncertainties resulting from the size of the sampled volume, and the uncertainties in the observed Hα luminosity. Table 2 lists the Schechter parameters and their uncertainties.

### 5.2. Parameter Evolution and Impact of Selection Criteria

Figure 12 compares the Schechter function parameters of SHELS with fixed \( \alpha = -1.20 \) with other Hα surveys. Evolution in the characteristic luminosity \( L^* \) is clearly visible.

The selection of galaxies by apparent R-band magnitude does not yield the same sample of galaxies obtained when
must investigate the potential systematic effects of the selection criteria ($R_{\text{tot}} \leq 20.3$ and $f_{\text{H}\alpha} \geq 10^{-15.5} \text{ erg s}^{-1} \text{ cm}^{-2}$) on the H$\alpha$ luminosity function.

From a given luminosity function ($\alpha = -1.20$, $\log L^*$(erg s$^{-1}$) = 42.00 and $\log \phi^*$(Mpc$^{-3}$) = $-2.75$), we construct a sample of galaxies with a flux $f_{\text{H}\alpha} \geq 10^{-15.5} \text{ erg s}^{-1} \text{ cm}^{-2}$. We choose these parameters because they are close to our recovered parameters from SHELS. Furthermore, we keep the parameters constant over our redshift range to test whether our selection criteria introduce an artificial evolution to the parameters. We assume a uniform galaxy distribution in a comoving volume. We assign each simulated galaxy an absolute magnitude using the distribution of absolute magnitude as function of $L_{\text{H}\alpha}$ in Figure 11. We calculate the apparent magnitude using the allocated redshift and a $k$-correction based on the observed distribution as a function of redshift. We apply the survey selection criterion of $R_{\text{tot}} \leq 20.3$ and recover the Schechter parameters using the STY-method. Figure 13 and Table 3 give the results.

When we keep $\alpha$ fixed in fitting the simulations, there is an artificial trend of increasing $L^*$ and decreasing $\phi^*$ with increasing redshift. This trend results from selective removal of the fainter H$\alpha$ galaxies. The removal would otherwise result in $\alpha$ decreasing (which we also show for $\alpha$ unconstrained). Thus, $L^*$ and $\phi^*$ should be corrected for the fact that $\alpha$ is kept fixed at a steeper value than would be fitted. However, the simulated trend in $L^*$ and $\phi^*$ is far smaller ($\Delta \log L^* = 0.33$, $\Delta \log \phi^* = -0.20$).

### Table 3

| Redshift Range | Fixed $\alpha$ | Unconstrained $\alpha$ |
|----------------|----------------|-------------------------|
|                | $\alpha$ | $\log L^*$ | $\log \phi^*$ | $\alpha$ | $\log L^*$ | $\log \phi^*$ |
| Input parameters | -1.20 | -2.75 | -1.20 | 42.00 | -2.75 |
| $0.010 \leq z < 0.100$ | -1.20 | 42.01 ± 0.07 | -2.75 ± 0.02 | -1.18 ± 0.04 | 49.18 ± 0.10 | -2.71 ± 0.08 |
| $0.100 \leq z < 0.200$ | -1.20 | 42.06 ± 0.03 | -2.77 ± 0.01 | -1.07 ± 0.03 | 49.13 ± 0.04 | -2.60 ± 0.04 |
| $0.200 \leq z < 0.300$ | -1.20 | 42.18 ± 0.02 | -2.84 ± 0.01 | -0.73 ± 0.05 | 48.15 ± 0.03 | -2.43 ± 0.03 |
| $0.300 \leq z < 0.377$ | -1.20 | 42.33 ± 0.02 | -2.95 ± 0.01 | -0.17 ± 0.07 | 48.11 ± 0.03 | -2.38 ± 0.01 |

**Figure 11.** Distributions of $\log L_{\text{H}\alpha}$ as function of $M_R$ for each redshift bin. We use these distributions to assign an H$\alpha$ luminosity to the observed absolute magnitude and to assign an absolute magnitude to a simulated H$\alpha$ luminosity. This procedure enables us to determine the final uncertainties in the Schechter parameters and to study the influence of the survey selection criterion $R_{\text{tot}} \leq 20.3$.

(A color version of this figure is available in the online journal.)

**Figure 12.** Three Schechter parameters as a function of redshift and look-back time for SHELS for pure star forming galaxies (red, green, blue, and cyan points), SHELS combined with S08 (magenta point), and surveys at similar redshifts that also use H$\alpha$ as star formation indicator (black points).

(A color version of this figure is available in the online journal.)
than we determine from the observations ($\Delta \log L^* = 1.11$, $\Delta \log \phi^* = -0.73$). Thus, the evolution in $L^*$ in Figure 12 is real.

When we fitted the simulations for all three parameters (unconstrained $\alpha$ in Table 3), the decrease of $\alpha$ ($\Delta \alpha = -1.01$) with increasing redshift is close to that of the observations ($\Delta \alpha = -0.72$; Table 2). Moreover, the faint-end slope from our lowest redshift bin (0.010 $< z < 0.100$, where the faint-end of the luminosity function is well sampled) is consistent with that of the combined luminosity function of SHELS and S08 at $z \sim 0.24$ (Section 4.2) within the uncertainties. Hence, we have no evidence for evolution of the faint-end slope over the redshift range covered by SHELS. The trend observed with the faint-end slope unconstrained is the result of our selection criteria.

We also notice an artificial trend in $L^*$ with increasing redshift for a constant luminosity function (although smaller than with $\alpha$ constrained) opposite to the trend observed, and opposite to the trend we derive fitting for $\alpha = -1.20$. To compensate for a shallow faint-end slope and a slight decrease in $L^*$ with redshift, $\phi^*$ increases in these simulations.

We do not consider $\phi^*$ because it only normalizes the luminosity function and does not determine the shape of it, unlike $\alpha$ and $L^*$. The normalization is dependent on the number of galaxies sampled. Because this number is heavily influenced by the distribution of galaxies (i.e., the large-scale structure; see Figure 4), it is not possible to say anything meaningful about any trend in $\phi^*$ even with the area covered by SHELS.

In summary, there is strong evidence for evolution in $L^*$ and no evidence for evolution in $\alpha$ over $0.100 < z < 0.377$.

5.3. The “True” $H\alpha$ Luminosity Function

In Section 5.2, we investigate the influence of our selection criteria on an assumed luminosity function. We can extend this application to determine the “true” H$\alpha$ luminosity function.

We construct a sample of galaxies with a flux $f_{H\alpha} \geq 10^{-15.5}$ erg s$^{-1}$ cm$^{-2}$ for a grid of given values of $\alpha$ and $L^*$. We constrain $\phi^*$ by the number of observed galaxies in each redshift bin. These choices are our input Schechter parameters. We apply our magnitude selection of $R_{\text{tot}} \leq 20.3$. Then we determine the output: the parameters one would recover using the STY-method. We take the median of the recovered Schechter parameters as our final output Schechter parameters. With these final output parameters, we determine the likelihood for our observations (Figure 10). We also show the input parameters and the confidence intervals from the likelihood-determination for each redshift bin (Figure 14).

Again, we find a significant evolution of $L^*$. $L^*$ increased toward higher redshifts, regardless of the inclusion of the lowest redshift results. Furthermore, there is no significant evolution in the faint end slope of the intrinsic $H\alpha$ luminosity function. These results confirm the findings in the Section 5.2. The evolution in $L^*$ is real and there is no evidence for evolution in $\alpha$.

Given the input $H\alpha$ luminosity function, we can calculate the selection function for each redshift bin. We define the selection function as the ratio of the measured data points in Figure 10 and the intrinsic or “true” $H\alpha$ luminosity function. The selection function measures the effect of our $R \leq 20.3$ selection criterion. We show the selection functions in Figure 15.

At $z \sim 0.24$, we also consider the data of S08. These data should be complete over the luminosity range covered...
by SHELS. We thus assume the data from the narrowband survey as the intrinsic Hα luminosity function and take the ratio between the S08 and the SHELS data as an estimate of the selection function (Figure 15; magenta long-dashed line). For consistency with the other redshift bins of SHELS we remove the OEW$_{\text{Hα}[\text{N} \text{ii}]}$ $\geq$ 12 Å constraint in this calculation (solid diamonds in Figure 9).

The selection function computed at $z \sim 0.24$ using S08 should lie on top of the SHELS selection function at 0.200 < $z$ < 0.300, but it does not. Thus, either SHELS underestimates—or S08 overestimates—the number of faint Hα galaxies. Either the $R$-band magnitude versus Hα–luminosity relation between SHELS and S08 must be significantly different, or there is another selection effect not yet considered. Figure 6 rules out a different $R$–Hα relation. This figure shows that the two surveys clearly overlap and do not have a significantly different $R$–Hα relation.

A selection effect that removes some galaxies from the SHELS sample is the OEW$_{\text{Hα}[\text{N} \text{ii}]}$ $\geq$ 12 Å criterion. Figure 9 shows the effect of this criterion; it slightly increases the number of galaxies at the faint-end of the SHELS luminosity function. This bias is, however, insufficient to explain the differences in the SHELS- and S08-based selection functions.

The narrowband survey of S08 may overestimate the number of fainter Hα galaxies. Even though consistent within the uncertainties, the faint-end slope of the combined luminosity function at $z \sim 0.24$ is somewhat steeper ($\alpha \sim -1.4$) than at our lowest redshift bin ($\alpha \sim -1.2$) causing a very steep selection function at $z \sim 0.24$.

We can determine the redshift of several narrowband-survey candidates of S08 using zCOSMOS DR2. Figure 16 shows the redshifts of the galaxies from S08 with confirmed redshifts near $z \sim 0.24$. Several galaxies have redshifts outside the wavelength range where the NB816 filter is sensitive to Hα at $z \sim 0.24$ (red line). About 25% of the candidates with spectroscopy are at a lower redshift $z \sim 0.21$. This redshift correspond to the wavelength range where the NB816 filter is sensitive to the [S II] $\lambda \lambda$6733,6718 doublet (blue lines). These galaxies belong to an overdensity in the large-scale structure at $z \sim 0.22$ (dotted histogram in Figure 16 and solid histogram in Figure 8).

Figure 17 shows the fraction of galaxies with redshifts corresponding to [S II] or Hα as a function of the S08 Hα luminosity. The figure suggests that the fraction of [S II] galaxies increases towards fainter luminosities. This effect could produce an excess of faint Hα galaxies in the S08 survey and thus could explain the difference in the selection functions implied by the SHELS simulations and the comparisons of SHELS and S08.

Color–color selections are sufficient to remove contaminating galaxies from the narrowband survey at higher redshifts. The contaminants include Hβ and [O III] at $z \sim 0.6–0.7$, [O II] at $z \sim 1.2$, and Lyα at $z \sim 5.7$ for a narrowband survey at $\sim$8150 Å (e.g., Fujita et al. 2003; Ly et al. 2007). However, it is impossible to distinguish Hα galaxies from [S II] galaxies by color (Westra & Jones 2008). The contamination is survey dependent because it depends on the details of the large-scale structure. The S08 survey is a case where there is a peak in the redshift distribution exactly where the narrowband survey is sensitive to [S II].

### 5.4 Volume Dependence

There is a large spread in the parameters determined from different surveys around $z \sim 0.24$ (Figure 12) accompanied by
To estimate the area required to constrain $L^*$ and $\phi^*$, we simulate many observed galaxies given a specific luminosity function at $0.233 < z < 0.251$ for different sized areas. We fitted the parameters with fixed $\alpha = -1.20$. On average, the parameters are very well recovered. However, for the smaller areas the spread in the recovered parameters is large. We show the 1$\sigma$ spread around the mean, the median, the inter-quartile range, and minimum and maximum values of the recovered values for each area in Figure 18.

If we assume that 10% is an acceptable uncertainty for a parameter ($\sim$0.04 in dex), then the survey area required is $\sim$3◦. Surveys like Fujita et al. (2003), Ly et al. (2007) and Westra & Jones (2008) at $z \sim 0.24$ are thus not large enough to constrain the bright end of the luminosity function. S08 is a factor of 2 shy of this area; SHELS is larger.

Hence, combining the S08 and SHELS data (Section 4.2) is an excellent way to constrain the faint and bright end of the luminosity function simultaneously.

### 6. Star Formation Density

We determine the star formation density ($\dot{\rho}$ in $M_\odot$ yr$^{-1}$ Mpc$^{-3}$) from the integrated H$\alpha$ luminosity density for each redshift range. We use the conversion from H$\alpha$ luminosity to SFR from Kennicutt (1998) for case B recombination and $T_e = 10^4$ K

$$\text{SFR} = 7.9 \times 10^{-42} L_{\text{H}\alpha},$$

where SFR in $M_\odot$ yr$^{-1}$ and $L_{\text{H}\alpha}$ in erg s$^{-1}$. We determine the H$\alpha$ luminosity density for $L \geq L_{\text{lim}}$ from the parameters of the Schechter function using

$$L = \phi^* L^* \Gamma \left( \alpha + 2, \frac{L_{\text{lim}}}{L^*} \right),$$

where $\Gamma$ is the incomplete gamma function.

The choice $L_{\text{lim}} = 0$ affects the integrated luminosity density.\footnote{$L_{\text{lim}} = 0$ reduces Equation (8) to $L = \phi^* L^* \Gamma(\alpha + 2)$, where $\Gamma$ is the complete gamma function.} Figure 19 shows the logarithm of the total luminosity density evaluated at $(\log L_{\alpha} / L^* + \alpha$) divided by the luminosity density at $(\log L_{\alpha} / L^* + \alpha = (-1, -1.35))$. We can thus determine the effect of using different limiting luminosities on the total luminosity density. For example, using $L_{\text{lim}} = 0$ for $\alpha = -1.35$ rather than $L_{\text{lim}} = 0.1 L^*$ gives a difference of $10^{0.12 - 0.00} = 1.31$, i.e. an increase of 30%. These effects are obviously more severe for steeper values of $\alpha$. When comparing surveys of different depths, one needs to be careful about extrapolations of the H$\alpha$ luminosity function (Schechter function) to very low SFRs, especially for steep $\alpha$.

Table 5 lists the star formation densities and uncertainties for SHELS down to the luminosity limit of the appropriate

| Redshift Range | $\alpha$ | $\log L^*$ | $\log \phi^*$ | Unconstrained $\alpha$ | $\log L^*$ | $\log \phi^*$ |
|---------------|---------|-----------|-------------|------------------------|-----------|-------------|
| 0.010 $\leq z < 0.100$ | -1.20 | 41.60$^{+0.13}_{-0.17}$ | -2.79$^{+0.13}_{-0.13}$ | -1.18$^{+0.11}_{-0.10}$ | 41.58$^{+0.23}_{-0.35}$ | -2.76$^{+0.26}_{-0.34}$ |
| 0.100 $\leq z < 0.200$ | -1.20 | 42.06$^{+0.06}_{-0.06}$ | -2.96$^{+0.07}_{-0.13}$ | -0.62$^{+0.10}_{-0.10}$ | 41.65$^{+0.18}_{-0.22}$ | -2.57$^{+0.28}_{-0.05}$ |
| 0.200 $\leq z < 0.300$ | -1.20 | 42.53$^{+0.10}_{-0.10}$ | -3.28$^{+0.12}_{-0.12}$ | -0.61$^{+0.15}_{-0.16}$ | 42.07$^{+0.21}_{-0.21}$ | -2.75$^{+0.07}_{-0.07}$ |
| 0.300 $\leq z < 0.377$ | -1.20 | 42.82$^{+0.04}_{-0.05}$ | -3.56$^{+0.03}_{-0.09}$ | -0.48$^{+0.17}_{-0.12}$ | 42.27$^{+0.04}_{-0.15}$ | -2.96$^{+0.02}_{-0.04}$ |
| 0.233 $\leq z < 0.251$ | -1.20 | 42.40$^{+0.22}_{-0.22}$ | -3.28$^{+0.07}_{-0.09}$ | -0.22$^{+0.44}_{-0.44}$ | 41.9$^{+0.31}_{-0.27}$ | -2.79$^{+0.20}_{-0.63}$ |

Figure 18. Box and whisker plot for the simulated surveys as a function of area. The surveys cover 0.233 $< z < 0.251$ and have a limiting flux of $10^{-15.5}$ erg s$^{-1}$ cm$^{-2}$. The gray box indicates the I$\sigma$ around the mean, the dash indicates the median, the boxes indicate the inter-quartile range, and the whiskers indicate minimum and maximum values of recovered Schechter parameters (using the STY-method) from the simulations.

very large uncertainties. All of these surveys (Fujita et al. 2003; Hippelein et al. 2003; Ly et al. 2007; Westra & Jones 2008) use a single or multiple narrowband filters over $\sim$300–950 $\square$. S08 uses 5540 $\square$. Typical volumes are 0.5–1 $\times 10^4$ Mpc$^3$; S08 covers 3 $\times 10^4$ Mpc$^3$. The smaller volumes are not large enough to constrain the bright end of the luminosity function. We discussed S08 in detail in Section 4.

To examine the impact of small volumes, we split SHELS into 16 separate pieces to match the area ($\sim$0.25 $\square$) of typical narrowband surveys that probe redshift $\sim$0.24. Table 4 gives the median recovered parameters and the inter-quartile range.

For $\alpha = -1.20$ the recovered parameters are almost identical to those of the entire field. The inter-quartile range is large, even when compared to the uncertainties in Table 2. If we combine the 16 “surveys,” we would have to increase the uncertainties in Table 2 because of the smaller number of galaxies, i.e., an increase in shot-noise. This uncertainty easily explains the scatter of the parameters observed at $z \sim 0.24$. It underscores the need for large-volume surveys to constrain the bright end of the luminosity function.

To constrain $\alpha$, it is more important to have a deep survey and to span a large range of luminosities rather than to cover a large area. The data from Ly et al. (2007) demonstrate this point. As discussed in S08, the data points from S08 and Ly et al. are quite similar at the fainter luminosities, both in slope and in amplitude. Thus, the survey area of Ly et al., i.e., $\sim$0.25 $\square$, can be large enough to constrain $\alpha$, and $\alpha$ only. Their area (volume) is too small to determine the bright end of the luminosity function (see also S08) because they do not observe enough of the rare most-luminous galaxies.
Table 5
Star Formation Density

| Redshift Range | $\log L_{\text{lim}}$ | $\log \dot{\rho}$ Fixed $\alpha$ | $\log \dot{\rho}$ Unconstrained $\alpha$ | $\log \dot{\rho}$ with $\log L_{\text{lim}} = 40$ Fixed $\alpha$ | $\log \dot{\rho}$ Unconstrained $\alpha$ |
|----------------|---------------------|-----------------------------------|-------------------------------------------|----------------------------------------|-------------------------------------------|
| $0.010 < z < 0.100^b$ | 37.84 | $-2.18 \pm 0.10$ | $-2.19 \pm 0.17$ | $-2.20 \pm 0.10$ | $-2.21 \pm 0.17$ |
| $0.100 < z < 0.200$ | 39.89 | $-1.92 \pm 0.09$ | $-1.92 \pm 0.12$ | $-1.93 \pm 0.09$ | $-1.92 \pm 0.12$ |
| $0.200 < z < 0.300$ | 40.55 | $-1.82 \pm 0.05$ | $-1.81 \pm 0.10$ | $-1.81 \pm 0.05$ | $-1.81 \pm 0.10$ |
| $0.300 < z < 0.377$ | 40.95 | $-1.82 \pm 0.03$ | $-1.82 \pm 0.08$ | $-1.80 \pm 0.03$ | $-1.81 \pm 0.08$ |
| $0.233 < z < 0.251^c$ | 41.21 | $-1.82 \pm 0.02$ | $-1.82 \pm 0.05$ | $-1.80 \pm 0.02$ | $-1.81 \pm 0.05$ |

Notes. We use the Schechter parameters determined for the pure star-forming galaxies in Table 2. We calculate the uncertainties using standard uncertainty propagation for Equation (8) and the uncertainties in Table 2. $\dot{\rho}$ is in $M_\odot$ yr$^{-1}$ Mpc$^{-3}$.

$^{a}L_{\text{lim}} = 4\pi D_l^2 \rho_{\text{lim}}$.

$^{b}$ The redshift range $0.010 < z < 0.100$ covers an atypical under-dense region (Section 2).

$^{c}$ Combined SHELS and S08 result.

We also show the star formation densities down to $\log L_{\text{lim}} = 40.00$ corresponding to a SFR of 0.079 $M_\odot$ yr$^{-1}$ for comparison with other surveys (Figure 20). We choose this value for all surveys because most surveys either reach this SFR, or the required extrapolation is modest. The solid symbols in Figure 20 represent surveys with star formation densities derived from the H$\alpha$ line; the open symbols come from either the [O ii] or [O iii] line. Figure 20 shows that the star formation density for other surveys at 0.200 < z < 0.300 is consistent with the star formation density determined from the combined luminosity function of SHELS and S08.

Figure 20 also shows a clear increase in the star formation density with increasing redshift. However, our lowest redshift point (0.010 < z < 0.100) lies below surveys at similar redshifts. This underestimate occurs because our field was selected against low redshift clusters. This survey is thus an underdense region at low redshifts and the star formation density is probably correspondingly underestimated.

Because we use the integrated Schechter function to determine the star formation density, the arguments in Section 5.4 apply redshift bin.
Figure 21. $D_{*}4000$ as a function of H$\alpha$ luminosity for each of the four redshift bins for pure star forming H$\alpha$ emitting galaxies.

Table 6

| Redshift Range | $\log \rho$ |
|----------------|-------------|
| $0.100 < z < 0.500$ | $-2.25^{+0.12}_{-0.23}$ |
| $0.500 < z < 0.900$ | $-1.96^{+0.13}_{-0.15}$ |
| $0.900 < z < 1.300$ | $-1.84^{+0.16}_{-0.13}$ |
| $1.300 < z < 1.700$ | $-1.78^{+0.03}_{-0.03}$ |
| $1.700 < z < 2.000$ | $-1.95^{+0.25}_{-0.26}$ |

Notes. The values for the star formation density are integrated down to log $L_{\text{lim}} = 40$.

Figure 22. Fraction of pure star forming galaxies with one or more neighbors for each redshift bin (colored histograms) as a function of redshift and the fraction for 0.01 < $z$ < 0.30 (black thick histogram). Colored triangles indicate $L^*$ (determined with $\alpha = -1.20$) for each redshift range.

(A color version of this figure is available in the online journal.)

7. PHYSICAL PROPERTIES OF STAR-FORMING GALAXIES

7.1. Stellar Population Age

In star-forming galaxies, the H$\alpha$ emission originates from gas surrounding the young stars. The spectrum from an actively star-forming galaxy is dominated by the light emitted by these young stars. Figure 21 shows $D_{*}4000$, the ratio of the continuum redward of the H$\alpha$ break and an indicator of the age of the stellar population (Balogh et al. 1999; Bruzual 1983), as a function of the H$\alpha$ luminosity for pure star-forming galaxies. A low $D_{*}4000$ ($D_{*}4000 \lesssim 1.44$; D. F. Woods et al. 2010, in preparation) indicates a young stellar population. The majority of the H$\alpha$ emitting galaxies contain a young stellar population.

for the Schechter parameters $L^*$ and $\phi^*$, are valid for the star formation density. The median, upper, and lower quartile range for the star formation density for 0.25 $\square$ subsets are in Table 6. Again, the recovered star formation density of a 0.25 $\square$ subset is almost identical to that of the entire field, but the standard deviation in the star formation density is very large (almost a factor of 2). The large uncertainty mainly results from the scatter in $L^*$ and $\phi^*$. Again, combined with the increased uncertainties resulting from increased shot-noise, the spread in star formation densities at narrow redshift slices can easily be explained by sampling a volume that is too small.

7.2. Galaxy–Galaxy Interaction

Sobral et al. (2009) find that the fraction of mergers rises with increasing luminosity particularly around $L^*$. Some of the SHELS galaxies are quite luminous in H$\alpha$ indicating they are undergoing a starburst. Barton et al. (2000) find that a close pass of two galaxies can initiate a starburst. Following Sobral et al., we examine the SHELS data to look for evidence of the impact of interactions on the H$\alpha$ luminosity function. Thus, we focus on galaxies that may have (or may have had) a recent encounter with another galaxy. We determine whether each galaxy has an apparently nearby “neighbor.”

A galaxy has a neighbor when the velocity difference (corrected for redshift) between the two galaxies is $\lesssim 500$ km s$^{-1}$, and their projected separation is $\lesssim 100$ kpc. These values are a standard definition of galaxy pairs (e.g., Barton et al. 2000; Patton et al. 2000; Lin et al. 2004; Woods & Geller 2007; Park & Choi 2009). We include the somewhat deeper SHELS catalog to look for neighboring galaxies (see Section 2). This catalog contains spectra of galaxies with magnitudes $20.3 < R < 20.6$ where the spectroscopy is 52% complete. The fraction of all our pure star forming galaxies that have a neighbor is 15.3% (547 out of 3565).9

Figure 22 shows the fraction of galaxies with one or more neighbors as a function of H$\alpha$ luminosity for the lowest three redshift bins (colored histograms) and for the three redshift ranges combined (thick black histogram). The fraction is always a lower limit; deeper spectroscopy might reveal only more neighbors of a galaxy, never fewer.

It is striking that the fraction of galaxies with neighbors increases around $L^*$ (and for the lowest redshift bin toward the lowest H$\alpha$ luminosities). This result agrees with a rise in the fraction of mergers with increasing H$\alpha$ luminosity found by Sobral et al. (2009). The interesting question for galaxy evolution is whether the location of the increase determines $L^*$, or whether $L^*$ determines the location of the increase.

9 If we decrease our projected separation criterion to 50 kpc, the fraction drops with a factor of $\sim 2$ to 7.4% (265 out of 3565). The fractions in Figure 22 scale with roughly the same factor within the uncertainties. Our conclusions are not affected by the choice of projected separation.
Figure 23. Magnitude difference between the galaxy and its neighbor as a function of $H\alpha$ luminosity for pure star forming $H\alpha$ emitting galaxies. The solid lines show $|\Delta m_{R}| = 2$, the demarcation between major and minor interactions. Galaxies above the dotted line are fainter than their neighbor; galaxies below are more luminous.

To investigate this behavior further, we investigate the magnitude difference between the galaxy and its neighbor(s). Figure 23 shows the $H\alpha$ luminosity as a function of the magnitude difference $\Delta m_{R} = R_{\text{galaxy}} - R_{\text{neighbor}}$.\footnote{For neighbors in the $R_{\text{out}} > 20.3$ catalog, we assumed $R = 20.3$. Thus, $\Delta m_{R} = R_{\text{galaxy}} - 20.3$ for these galaxies.} We also indicate the demarcation between minor and major pairs, i.e., $|\Delta m| = 2$ (e.g., Woods & Geller 2007).

Luminous $H\alpha$ galaxies with neighbors tend to be mostly part of a major pair, and to a lesser extent the more luminous galaxy of a minor pair; faint $H\alpha$ galaxies with neighbors can be part of a major or minor pair. However, when faint $H\alpha$ galaxies are part of a minor pair, they tend to be the fainter (smaller) galaxy. The behavior in Figure 23 is consistent with the picture of interaction-induced star formation. The increase in the fraction around $L_{*}$ implies that galaxy–galaxy interactions are important for the increase of the $H\alpha$ luminosity in these galaxies.

8. SUMMARY AND CONCLUSION

We use the SHELS to study $H\alpha$ emitting galaxies. SHELS is complete to $R_{\text{tot}} = 20.3$ over a large 4 $^\circ$ area. This area yields a large enough volume to study the bright end of the $H\alpha$ luminosity function as a function of redshift.

We determine the $H\alpha$ flux and attenuation from the SHELS spectroscopy. We also identify galaxies that host AGNs or are composites.

We combine the strengths of two surveys, the breadth of SHELS (to constrain the bright-end of the luminosity function) and the depth of the narrowband survey of S08 (to determine the faint end slope of the luminosity function), to determine a well-constrained $H\alpha$ luminosity function at $z \sim 0.24$. A narrowband survey goes deep over a limited field of view to cover the faint end of the luminosity function. A broadband selected spectroscopic survey can easily cover a larger volume to probe the bright end of the luminosity function. The resulting Schechter parameters are consistent with S08 within their uncertainties.

We determine the $H\alpha$ luminosity function from SHELS for four redshift intervals over $0.010 < z < 0.377$. The lowest redshift interval ($0.010 < z < 0.100$) covers an atypical underdense region due to field selection. The characteristic luminosity $L_{*}$ increases as a function of redshift ($\Delta \log L_{*} = 0.84$ over $0.100 < z < 0.377$).

The star formation density also increases with increasing redshift ($\Delta \log \dot{\rho} = 0.11$ over $0.010 < z < 0.377$). The SFR from the combined luminosity function of SHELS and S08 is consistent with that of SHELS alone at $0.200 < z < 0.300$.

The fraction of galaxies with neighbors increases by a factor of 2–5 around $L_{*}$ for the most luminous star-forming galaxies at each redshift, similar to Sobral et al. (2009). The fraction appears to also increase toward fainter $H\alpha$ luminosity as a result of interactions in minor pairs. We conclude that triggered star formation is important for both the highest and lowest luminosity $H\alpha$ galaxies.

The future of surveys for star-forming galaxies is a combination of a large-area spectroscopic survey combined with very deep narrowband imaging. However, the narrowband imaging requires extensive test spectroscopy because the impact of large-scale structure with respect to the filter response is unknown a priori. The combination of methods can constrain and remove the scatter in the star formation density as a function of redshift. The combination also allows a secure determination of the shape of the luminosity function over a large luminosity range.

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Facilities: MMT (Hectospec)

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