1. INTRODUCTION

The rate at which stars form on a cosmic scale is a fundamental property of the universe. Various efforts have shown the cosmic star formation rate per unit comoving volume to significantly rise from the current epoch back to a redshift of 1, evolving at the rate of ρ_{SFR}(z) ∝ (1 + z)^α, where α is estimated to lie between 1.5 and 4 (e.g., Lilly et al. 1996; Cowie et al. 1999; Wilson et al. 2002; Gallego et al. 2002; Tresse et al. 2002; Hippelein et al. 2003; Hopkins 2004; Pérez-González et al. 2005; Le Floc’h et al. 2005; Hanish et al. 2006; Babbedge et al. 2006; Villar et al. 2008; Magnelli et al. 2009). Reliably constraining γ will assist in interpreting models of galaxy evolution, since the cosmic star formation history is intimately tied to the buildup of heavy metals and stellar mass over time (Pei & Fall 1995; Madau et al. 1996; Pei et al. 1999; Somerville et al. 2001; Cole et al. 2001; Panter et al. 2003). In fact, predictions of the accumulated stellar mass based on the integrated cosmic star formation history exceed the observed stellar mass at the present epoch by a factor of 2 (Figure 1 of Wilkins et al. 2008). From an observational viewpoint, the evolutionary parameter γ is ideally measured by uniformly sampling the star formation rate using a large sample of galaxies spanning multiple fields and multiple epochs between z = 0 and z ∼ 1 − 2. The Wyoming Survey for Hα, or WySH, surveys hundreds of galaxies at four intermediate redshifts, covering three separate fields that total some 4 deg^2 (Dale et al. 2008; hereafter D08). WySH utilizes Hα to probe the star formation in galaxies, an optical emission line that directly traces massive star formation, is technically simple to observe, and lies at a relatively long wavelength to help minimize the effects of extinction internal to star-forming galaxies. The survey has been carried out where redshifted Hα can be detected at wavelengths over which CCDs are sensitive: z ∼ 0.16, 0.24, 0.32, and 0.40. This optical observing program is complemented by NewHα, a collaborative near-infrared narrowband imaging survey of Hα at redshifts of z ∼ 0.81 and 2.2 using the wide-field NEWFIRM camera (Probst et al. 2004) on the Kitt Peak National Observatory 4 m telescope (J. Lee et al. 2010, in preparation; C. Ly et al. 2010, in preparation). The NewHα survey includes observations through low airglow windows at 1.19 and 2.10 μm, sampling the Hα luminosity function down to levels similar to that explored in WySH. NewHα also has an extensive follow-up multi-slit spectroscopy campaign with the 6.5 m Baade telescope at Las Campanas Observatory, allowing us to verify Hα-emitting candidates, directly measure internal extinction via Balmer line ratios, probe metal abundances, and to identify AGN (L. Momcheva et al. 2010, in preparation). The combination of these two surveys will provide powerful constraints on the evolution in the Hα luminosity function and the cosmic star formation rate over 0 ≲ z ≲ 2.2. This Letter summarizes results from the WySH observing program, including Hα luminosity functions at four intermediate redshifts, a measure of the evolution in the volume-averaged cosmic star formation rate over these same epochs, and an estimate of the impact of cosmic variance. Section 2 reviews the survey parameters; Section 3 presents results from all epochs; and Section 4 provides a summary. We assume H_0 = 70 h_{70} km s^{-1} Mpc^{-1}, Ω_m = 0.3, and Ω_λ = 0.7.
2. THE SURVEY

WySH is a multi-epoch narrowband imaging survey for redshifted $H\alpha$ carried out on the Wyoming Infrared Observatory 2.3 m telescope (WIRO). The survey spans multiple “blank” fields selected to minimize foreground contamination by zodiacal and Galactic dust, bright stars, and nearby galaxies. Observing multiple fields also aids in minimizing the impact of cosmic variance, a catch-all term for the statistical fluctuations inherent to observations of different regions at cosmological distances. By design, two of these fields, ELAIS-N1 and the Lockman Hole, overlap with the target areas of deep infrared and ultraviolet surveys. The SWIRE Spitzer Legacy project provides maps of these regions using several bandpasses between 3 and 160 $\mu$m (Lonsdale et al. 2003) along with a wealth of ancillary data at other wavelengths. The Galaxy Evolution Explorer (GALEX) Deep Imaging Survey (Martin et al. 2005) includes the ELAIS-N1 and Lockman Hole fields, providing two channels of ultraviolet data from integrations that are 300 times longer than the standard integration of that mission’s all-sky survey. The third WySH field, also known as “WySH 1.1,” conveniently fills the right ascension gap between the Lockman Hole and the ELAIS-N1 field to enable year-round observations from WIRO (D08; Table 1). While the main goal of this survey is to provide a statistically robust measure of the evolving star formation history of the universe at intermediate redshifts, the combination of the surveys described above enables interesting parallel science. For example, combining $H\alpha$, ultraviolet, and infrared data allows us to study the evolution over time of the average attenuation by interstellar dust within star-forming galaxies (Moore et al. 2010).

2.1. Observations and Data Processing

WIRO is equipped with a prime focus CCD camera with 0’523 pixels and a 17’9 field of view (Pierce & Nations 2002). Redshifted $H\alpha$ emission is observed in four separate cosmological epochs, $z \approx 0.16, 0.24, 0.32,$ and 0.40. This survey differs from traditional narrowband imaging surveys by using nearly identical and wavelength-adjacent narrowband filter pairs ($\sim$60 Å FWHM). If a source’s redshift places the $H\alpha$ emission to appear in Filter A, then the emission detected from Filter B is used to subtract off the stellar continuum as detected by Filter A. Likewise, the reverse applies if $H\alpha$ is found in Filter B. The basic unit of observation is a 300 s frame, though several are taken for each filter at each location. After the pre-processing of individual frames (e.g., bias subtraction, flat-fielding, and fringing correction; see Section 2.3 of D08), the multiple 300 s frames for a given field are aligned and stacked to create images with longer effective integrations. The effective multiple 300 s frames for a given field are aligned and stacked to achieve a similar sensitivity to line luminosity at each epoch: the $H\alpha$ luminosity-dependent prescription of Hopkins et al. (2001; though also see Garn et al. 2010). Photometric redshifts are used to cull the contaminators. Multiple photometric redshift catalogs are available for the fields pursued in this work: Rowan-Robinson et al. (2008) from SWIRE, Csabai et al. (2003) from Sloan Digital Sky Survey (SDSS), and from our own suite of deep observations from WIRO covering $UBVRI$ (15–75 minute integrations) and narrowband imaging at eight wavelengths between 7597 and 9233 nm. WIRO-based photometric redshifts are estimated using the Le Phare code7 and a suite of spiral, elliptical, irregular, and starburst templates (the CWW_KINNEY templates), allowing the V-band extinction to vary from 0 to 3 mag. For the sake of uniformity, SWIRE photometric redshifts are used where available, with SDSS and our own photometric redshifts employed to supplement the SWIRE coverage.

3. RESULTS

3.1. $H\alpha$ Luminosity Functions

The $H\alpha$ luminosity function for each epoch is displayed in Figure 1. The amplitude of the $j$th bin of each luminosity function and its uncertainty are derived from

$$\Phi(z, \log L_j) = \frac{\sum V(z_j, L_j)^{-1}}{\Delta \log L},$$

$$e[\Phi(z, \log L_i)] = \sqrt{\frac{\sum V(z_j, L_j)^{-2}}{\Delta \log L}},$$

(1)

where $V(z_j, L_j)$ is the comoving volume for the $j$th galaxy in the summation. The luminosities are binned according to $|\log L_j - \log L_i| < \frac{1}{2} \Delta \log L$, with a luminosity bin width $\Delta \log L$ spanning 0.4 dex. Several corrections described in Section 3 of D08 are incorporated into the luminosity functions displayed in Figure 1. The luminosity functions are corrected for sample incompleteness ($k(z, L_{min})$, filter transmission characteristics, and $H\alpha$ line extinction ($e^{H\alpha}$) following the $H\alpha$ luminosity-dependent prescription of Hopkins et al. (2001; though also see Garn et al. 2010). A bin-by-bin tabulation of the incompleteness and extinction corrections are provided in Table 1. Open circles in Figure 1 indicate the data corrected for all issues described above except incompleteness; the filled circles also include corrections for incompleteness. Error bars in Figure 1 reflect the uncertainty in the luminosity function amplitude according to Equation (1), summed in quadrature with the uncertainties in the incompleteness corrections. Also included in

7 http://www.oamp.fr/people/arnouts/LE_PHARE.html
Figure 1. Luminosity functions at $z \approx 0.16, 0.24, 0.32,$ and 0.40 based on $214+424+438+91$ Hα-emitting galaxies. The data without incompleteness corrections are displayed as open circles, while those corrected for incompleteness are shown as filled circles. Error bars reflect the uncertainty in the luminosity function amplitude. The thick solid lines show the Schechter fits for the parameters presented in the first four rows of Table 2. Literature fits are also provided at $z \sim 0.16$ (Sullivan et al. 2000; Westra et al. 2010), $z \sim 0.24$ (Tresse & Maddox 1998; Fujita et al. 2003; Ly et al. 2007; Shioya et al. 2008), and $z \sim 0.40$ (Ly et al. 2007).

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

Table 1

| Redshift | $\log L_{\alpha}$ (erg s$^{-1}$) | $\kappa(z, L_{\text{inc}})$ | $\phi_{\text{inc}}(z, L_{\text{inc}})$ |
|---------|-----------------|-----------------|-----------------|
| 0.16    | 42.0 ± 0.1      | 0.02 ± 0.02     | 0.01 ± 0.01     |
| 0.24    | 41.8 ± 0.1      | 0.01 ± 0.02     | 0.01 ± 0.01     |
| 0.32    | 42.2 ± 0.1      | 0.00 ± 0.02     | 0.02 ± 0.01     |
| 0.40    | 42.3 ± 0.1      | 0.00 ± 0.02     | 0.02 ± 0.02     |

Table 2

| Redshift | $\alpha$ | $\log L_{\alpha}$ (H$_{\alpha}$ ergs s$^{-1}$) | $\log \phi_{\alpha}$ (H$_{\alpha}$ ergs$^{-3}$) | $\frac{\beta_{\text{SFR}}}{M_{\odot}}$ |
|---------|---------|-----------------|-----------------|---------------|
| 0.16    | -1.38   | 42.0 ± 0.1      | 3.08 ± 0.02     | 0.010 ± 0.001 |
| 0.24    | -1.38   | 41.8 ± 0.1      | 2.70 ± 0.02     | 0.013 ± 0.001 |
| 0.32    | -1.38   | 42.2 ± 0.1      | 2.90 ± 0.01     | 0.021 ± 0.001 |
| 0.40    | -1.38   | 42.3 ± 0.1      | 2.97 ± 0.04     | 0.024 ± 0.002 |

Note. * Fixed; not fitted.

Figure 1 are Hα-based luminosity functions from the literature, largely consistent with our results.

Going down to and including these limiting luminosities, a Schechter profile (Schechter 1976) is fit to the incompleteness-corrected luminosity functions:

$$\Phi(z, \log L) \propto \frac{L}{L_{\alpha}(z)} \phi_\alpha(z) \left( \frac{L}{L_{\alpha}(z)} \right)^{\alpha(z)} e^{-L/L_{\alpha}(z)} \delta(z),$$

where $\alpha(z)$ conveys the shape of the function, $L_{\alpha}(z)$ sets the luminosity scale, and $\phi_\alpha(z)$ represents the overall normalization. The parameters for the functional fits displayed in Figure 1 are listed in the first four rows of Table 2. Since the faint-end slopes are difficult to gauge from the available luminosity bins for the two earliest epochs, for these solutions we have fixed $\alpha(z) \approx 0.32$ and $\alpha(z) \approx 0.40$ to be the same as the average of that found for the later two epochs ($\approx 0.38$). Also included in Table 2 are solutions allowing all parameters to vary. In all cases, Monte Carlo simulations are employed to estimate the average fit parameters and their uncertainties (see Figure 2). Each fit is repeated 10,000 times after using the measured luminosity uncertainties to randomly add a (Gaussian deviate) offset to each Hα luminosity. The standard deviations in the simulations are used to represent the luminosity function parameter uncertainties.

Extremely deep surveys are required to adequately measure the faint-end slopes of the luminosity function (e.g., Ly et al. 2007). As can be seen from Figure 1, the lowest luminosities for which $\Phi(z, \log L)$ are reliably obtained increase with redshift: $\log L_{\text{lim}}(\text{H}\alpha \text{ ergs s}^{-1}) = \{40.2, 40.6, 41.0, 41.4\}$ for $z \approx \{0.16, 0.24, 0.32, 0.40\}$. While the fitted values for $\alpha(z)$ are somewhat steeper for $z \approx 0.16$ and 0.24 than at the two earlier epochs (see...
Figure 2. 2σ (95.4%) confidence distributions of the luminosity function parameters α and \( L_* \) for 10,000 Monte Carlo simulations of the data, for the case where all parameters are allowed to vary (rows 5–8 of Table 2). The redshifts are indicated within the contours.

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

rows 5–8 in Table 2), this result is very tenuous since there are too few low luminosity galaxies detected at \( z \approx 0.32 \) and 0.40 to adequately constrain the faint-end slopes.

In terms of the other luminosity function parameters, \( L_*(z) \) and \( \phi_*(z) \), Westra et al. (2010) show that intermediate redshift surveys like WySH that span at least 3 deg\(^2\) cover large enough volumes to effectively constrain the bright end of the luminosity function. For our standard solutions involving a fixed slope of \( \alpha = -1.38 \) and luminosity-dependent internal extinction, the changes in the luminosity function with redshift are mainly driven by changes in the characteristic luminosity \( L_*(z) \), with the average \( L_*(z) \) being a factor of 2 larger for the two earlier epochs than the average measured at \( z \approx 0.16 \) and 0.24. It is more difficult to discern any systematic evolutionary changes in the source number density as parameterized by the luminosity function amplitude \( \phi_*(z) \).

3.2. The Evolution in the Cosmic Star Formation Density

The volume-averaged cosmic star formation rate can be computed by integrating under the fitted Schechter function and multiplying by the Kennicutt (1998) star formation rate calibration:

\[
\dot{\rho}_{\text{SFR}}(z) \equiv \left( h_70 \right) \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3} = 7.9 \times 10^{-42} \, \mathcal{L}(z) \times (h_70 \text{ ergs s}^{-1} \text{ Mpc}^{-3}),
\]

where an analytical expression for the luminosity density is

\[
\mathcal{L}(z) = \int_0^\infty dL \, (z) \, \phi_*(z) \, L_*(z) \Gamma(\alpha + 2).
\]

Table 2 provides the integrated cosmic star formation rate densities. There is a clear, systematic increase in \( \dot{\rho}_{\text{SFR}}(z) \) with redshift, with an overall difference of a factor of \( \sim 2 \) between \( z \approx 0.16 \) and \( z \approx 0.40 \). This result is robust to the effects of cosmic variance, fluctuations due to the characteristics of the particular volume(s) being probed along a survey’s line(s) of sight (e.g., clusters, voids, etc.): the values for \( \dot{\rho}_{\text{SFR}}(z) \) extracted from individual fields (e.g., Lockman Hole and ELAIS-N1) differ by only \( \sim 20\% \). Placed in a larger context, our values for \( \dot{\rho}_{\text{SFR}}(z) \) fit well within the envelope determined by previous emission line surveys (see Figure 3 and the citations in the caption). If the evolution over \( 0 \lesssim z \lesssim 1.5 \) is cast in a power-law form, \( \dot{\rho}_{\text{SFR}}(z) \propto (1+z)^\gamma \), the exponent is best fit by \( \gamma = 3.4 \pm 0.4 \). This slope is consistent with the typical values (3 \( \lesssim \gamma \lesssim 4 \)) found in the literature for this redshift range.

4. DISCUSSION AND SUMMARY

The primary aim of the Wyoming Survey for \( \text{H}_\alpha \), or WySH, is to accurately quantify the \( \text{H}_\alpha \) luminosity function via narrow-band imaging spanning \( \lesssim 4 \text{ deg}^2 \) and multiple cosmic epochs. Important features of the survey include the use of narrow-band filter pairs at each epoch for improved stellar continuum subtraction and the spatial overlap with deep ultraviolet and infrared surveys that enable interesting follow-up studies. Butressed by a total of nearly 1200 \( \text{H}_\alpha \) detections, we find a modest evolution in the \( \text{H}_\alpha \) luminosity function over \( z \approx 0.16, 0.24, 0.32, \) and 0.40. The values of the volume-averaged cosmic star formation rate, found by integrating under the luminosity functions, change by a factor of 2 over this moderate stretch in redshift. Our results indicate that this evolution is largely driven by changes in the characteristic luminosity \( L_* \), which also shows an evolution by a factor of 2 over these epochs. That the evolution in the cosmic star formation rate density over these
intermediate redshifts is mainly influenced by systematic changes in the characteristic luminosity is consistent with the findings of Le Floc’h et al. (2005), Pérez-González et al. (2005), Magnelli et al. (2009), and Westra et al. (2010), though Ly et al. (2007) find the evolution to be more driven by changes in the source number density. Placing our results in the larger context of the slew of recent emission line surveys for $\dot{\rho}_{\text{SFR}}$ over $0 \lesssim z \lesssim 1.5$, the evolution in the cosmic star formation rate density is estimated to be $\dot{\rho}_{\text{SFR}}(z) \propto (1 + z)^{3.4 \pm 0.4}$. Results from a complementary near-infrared narrowband imaging survey of Hz-emitters will extend this work to redshifts of $z \sim 0.81$ and 2.2. Finally, the large volume covered by this optical survey enables a measure of the impact of cosmic variance. By separately analyzing the different fields in this survey, in particular the Lockman Hole and ELAIS-N1, we find a variation in $\dot{\rho}_{\text{SFR}}$ at the 20% level for any given redshift.

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