THE REST-FRAME OPTICAL SPECTRUM OF MS 1512−cB58\(^1\)

**Harry I. Teplitz,\(^2,3\) Ian S. McLean,\(^4\) E. E. Becklin,\(^5\) Donald F. Figer,\(^6\) Andrea M. Gilbert,\(^6\) James R. Graham,\(^6\) James E. Larkin,\(^4\) N. A. Levenson,\(^7\) and Mavourenek K. Wilcox\(^4\)****

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**ABSTRACT**

Moderate-resolution, near-IR spectroscopy of MS 1512−cB58 is presented, obtained during commissioning of the near-infrared spectrometer (NIRSPEC) on the Keck II telescope. The strong lensing of this \(z = 2.72\) galaxy by the foreground cluster MS 1512+36 makes it the best candidate for detailed study of the rest-frame optical properties of Lyman-break galaxies. In 80 minutes of on-source integration, we have detected H\(\alpha\), [N\(\text{II}\)] \(\lambda\lambda 6583, 6548\), [O\(\text{I}\)] \(\lambda 6300\), He\(\text{I}\) \(\lambda 5876\), [O\(\text{III}\)] \(\lambda\lambda 5007, 4959\), H\(\beta\), H\(\gamma\), [O\(\text{II}\)] \(\lambda 3727\), and a strong continuum signal in the range of 1.29–2.46 \(\mu\)m. A redshift of \(z = 2.7290 \pm 0.0007\) is inferred from the emission lines, in contrast to the \(z = 2.7233\) calculated from UV observations of interstellar absorption lines. Using the Balmer line ratios, we find an extinction of \(E(B-V) = 0.27\). Using the line strengths, we infer a star formation rate (SFR) of \(620 \pm 18\) \(M_{\odot}\) yr\(^{-1}\) \((H_\alpha = 75, q_\odot = 0.1, \text{ and } \Lambda = 0)\), which is a factor of 2 higher than that measured from narrowband imaging observations of the galaxy but is a factor of almost 4 lower than the SFR inferred from the UV continuum luminosity. The width of the Balmer lines yields a mass of \(M_{\text{vir}} = 1.2 \times 10^{10} M_{\odot}\). We find that the oxygen abundance is \(1/4\) solar, in good agreement with other estimates of the metallicity. However, we infer a high nitrogen abundance, which may argue for the presence of an older stellar population.

**Subject headings:** cosmology: observations — galaxies: evolution — galaxies: individual (MS 1512−cB58)

1. INTRODUCTION

The largest sample of high-redshift galaxies was selected from observations of the extinction of rest-frame far-ultraviolet light by intrinsic and intergalactic absorption. These Lyman-break galaxies (LBGs; Steidel et al. 1996) may be the tracers of the global star formation history of the universe (Madau, Pozzetti, & Dickinson 1998). However, the unquantified effects of dust extinction present an obstacle to such an interpretation. For example, corrections to the star formation rate (SFR) of LBGs have been suggested to be as large as factors of 2–10 (Pettini et al. 1998, hereafter P98; Trager et al. 1997).

In this Letter, we present the first observations of an LBG with the near-infrared spectrometer (NIRSPEC) on the Keck II telescope. We will use the rest-frame optical spectrum to obtain a model-independent measure of dust extinction, an estimate of the virial mass, and the star formation rate. Spectra such as this one also provide the best method for determining the metal abundance in LBGs. We will examine the evolutionary status of cB58 and its implications as a “typical” LBG.

We have chosen the brightest LBG as our first target (MS 1512−cB58; see Yee et al. 1996a). MS 1512−cB58 is a gravitationally lensed starburst galaxy at \(z = 2.72\). It was discovered serendipitously, within the field of the \(z = 0.37\) galaxy cluster MS 1512+36, in spectra obtained for the Canadian Network for Observational Cosmology survey (Yee, Ellington, & Carlberg 1996b). MS 1512−cB58 is clearly extended with the morphological characteristics of a lensed arc (Williams & Lewis 1996; Seitz et al. 1998). It has an ultraviolet spectrum representative of LBGs, but due to a factor of \(\sim 30\) magnification (Seitz et al. 1998), it is orders of magnitude brighter than any other object of its kind (\(V = 20.6, K' = 17.8\); Ellington et al. 1996, hereafter E96). Like most LBGs, its UV spectrum (devoid of strong, high-ionization emission lines) rules out any nonstellar (active galactic nucleus) contribution to its flux. Its apparent (lensed) star formation rate is \(2417\) \(M_{\odot}\) yr\(^{-1}\) \((H_\alpha = 75, q_\odot = 0.1, \text{ and } \Lambda = 0)\); with extinction correction) from the 1500 \(\AA\) continuum (Pettini et al. 2000, hereafter P2000). Throughout this Letter, unless otherwise noted, a cosmology of \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\), \(q_0 = 0.1\), and \(\Lambda = 0\) is assumed.

2. OBSERVATIONS

Near-IR spectra were obtained using the NIRSPEC instrument on the 10 m W. M. Keck II telescope (McLean et al. 1998). Spectra were obtained in the low-resolution, long-slit mode, using a slit width of 3 pixels (0.057) at the (InSb) detector. Observations were made in the H and K bands and in the wavelength range 1.3–1.6 \(\mu\)m (hereafter N4 for the custom NIRSPEC-4 filter). The seeing was at 0.4, 0.4, 0.6 for N4, H, and K respectively. MS 1512−cB58 is highly elongated, with a major axis \(\sim 20^\prime\) long but a minor axis only a few tenths of an arcsecond wide. The slit was aligned with the long axis, while the unresolved (seeing-broadened) width filled the slit. H-band spectra were obtained in 300 s exposures separated by \(\sim 10^\prime\) nodding along the slit; N4-band and K-band spectra were taken in 600 s integrations. Total integration times were 1200, 1800, and 1800 s in N4, H, and K, respectively.

The data reduction procedure followed the steps outlined in McLean et al. (2000). Wavelength calibration was good to 0.99 \(\AA\). The output pixel scale was 4.16 \(\AA\) pixel\(^{-1}\) in \(H\) and...
Fig. 1.—N4-band spectrum of MS 1512—cB58, with 20 minutes of integration time. Detected emission lines are indicated. The dotted lines show the locations of OH sky lines with residuals that are visible in the two-dimensional spectrum. The lower spectrum shows the 1σ errors, truncated at 14 × 10⁻¹⁷ ergs cm⁻² s⁻¹ Å⁻¹ for clarity and arbitrarily shifted downward on the plot. The increases in the errors occur at the position of the night-sky lines and at positions of high atmospheric extinction.

K and 2.08 Å pixel⁻¹ in N4. Unresolved argon arc-lamp lines had FWHM = 13.7 Å for a final resolution of, for example, R = 1300 at 1.8 μm. Nodded frames were registered, and the final one-dimensional spectrum was extracted using a Gaussian optimal extraction filter. Extracted spectra were divided by the atmospheric absorption correction. We obtained this spectrum from a similarly reduced observation of a mostly featureless star (HR 5569, an A2 V for the K band; PPM 130690, a G star for the H band; and HR 5630, an F8 V star for the N4 band), divided by a Kurucz (1993) model atmosphere. Emission-line equivalent widths (EWs) were measured using Gaussian fits to the line after subtraction of a local continuum. The errors are truncated and shifted downward on the plot. The “break” in the continuum at 1.82 μm is a residual from the atmospheric absorption correction, not a drop in the galaxy’s SED.

Fig. 2.—H-band spectrum of MS 1512—cB58, with 30 minutes of integration time. As in Fig. 1, the 1σ errors are truncated and shifted downward on the plot. The “break” in the continuum at 1.82 μm is a residual from the atmospheric absorption correction, not a drop in the galaxy’s SED.

Fig. 3.—K-band spectrum of MS 1512—cB58, with 30 minutes of integration time. As in Fig. 1, the 1σ errors are shifted downward on the plot. The image of the highest surface brightness part of the source galaxy (Seitz et al. 1998); as such, our measurements of the EW can scale directly to the photometry since light lost outside the slit is just a pure fraction of the total light. No real features fall outside the slit, as might be expected for an unlensed galaxy.

3. Results

The complete 1.28—1.53, 1.55—1.97, and 2.05—2.46 μm spectra of MS 1512—cB58 are shown in Figures 1, 2, and 3, respectively. Just as LBG spectra in the rest-frame UV are remarkably similar to nearby starbursts, so too the optical spectrum of MS 1512—cB58 is very similar to local irregular or late-type spiral galaxies. Table 1 lists the wavelengths and fluxes of the measured emission lines.

The mean redshift calculated from the emission lines is z = 2.7290 ± 0.0007, in contrast to the z_{abs} = 2.7233 ± 0.0014 reported in Yee et al. (1996a) from the rest-frame UV interstellar absorption lines. P98 find that velocity shifts on the order of several hundred kilometers per second between interstellar absorption lines and H β emission lines are typical in LBGs. P2000 confirm that this shift is seen in MS 1512—cB58 as well, finding z_{em} = 2.7296 ± 0.0012. Since the measurement of the systemic redshift of MS 1512—cB58 has only recently been available, several observations have been made in recent years assuming z_{em} = z_{abs} (e.g., Bechtold et al. 1997; Frayer et al. 1998).

### Table 1

| Line       | λ_{rest} (μm) | z_{em} | W_{em} (Å) | F*   |
|------------|---------------|--------|------------|------|
| [O III] λ5007 | 1.86678       | 2.72845 | 97 ± 5  | 14.73 ± 0.78 |
| [O III] λ5007 | 1.84913       | 2.72890 | 26 ± 8  | 4.01 ± 1.30   |
| [H β] λ4861   | 1.81217       | 2.72774 | 26 ± 4  | 4.07 ± 0.57   |
| [Hγ] λ4340    | 1.61828       | 2.72875 | 9 ± 1   | 1.61 ± 0.17   |
| [Hδ] λ4101    | 1.58764       | 2.72873 | 3 ± 1   | 1.22 ± 0.22   |
| [O II] λ3726   | 1.3898        | 2.72897 | 37 ± 3  | 12.47 ± 1.22  |
| [O II] λ3726   | 1.34437       | 2.72897 | 37 ± 3  | 12.47 ± 1.22  |

*Observed line flux in units of 10⁻¹⁶ ergs s⁻¹ cm⁻².

*The blue wing of the 4959 Å line is in a deep atmospheric absorption trough.
metallicity regime (McGaugh 1991). So, following KKP99, we use the relationship between the [O III] λ5007/[N II] λ6584 = 10^{−1.6} ratio and the oxygen abundance to confirm that the inferred metallicity is reasonable (Edmunds & Pagel 1984).

The solar value of 12 + log (O/H) is 8.89, and thus cB58 has a metallicity that is 0.32 solar, which is broadly consistent with the Z/Z⊙ ≈ 0.25 found by P2000. Frayer et al. (1997) find a similar result, Z/Z⊙ ≈ 0.2–0.6, based on the spectral energy distribution (SED) and extinction.

The emission-line ratios also yield the nitrogen abundance in MS 1512−cB58. The N/O ratio is typically assumed to be equal to the N^+/O^- ratio. Using our estimates above, we can calculate N/O if we assume an electron temperature that is consistent with the oxygen abundance. Using KKP99’s Figure 5, we find that T_e(O^+) = 9800 K, and then from Vila-Costas & Edmunds (1992, hereafter VCE), we infer that T_e(O^+) = 11,400 K from their Table 1 and that

$$\log \left( \frac{N^+}{O^-} \right) = \log \frac{F_{6584} + F_{6548}}{F_{O^+}} + 0.307 - 0.02 \log t_{O^+} - \frac{0.726}{t_{O^+}},$$

(2)

where \( t_{O^+} = T_e(O^+)/10^4 \). Thus, we find that \( \log (N^+/O^-) = -1.24 \). This value of the nitrogen abundance is well below the solar value, consistent with the metallicity inferred from the oxygen abundance. However, the nitrogen abundance is still higher than might be expected for a galaxy as young as MS 1512−cB58 has been predicted to be. The oxygen/nitrogen abundance ratio is most consistent with local (≫1 Gyr old) Sd galaxies (VCE), although within the observed range of local, possibly younger, irregular galaxies. Furthermore, the relatively high nitrogen abundance suggests that an older population of stars is necessary to produce it. The ratio log (N/O) > −1.4 suggests the presence of a secondary phase of nitrogen production, from intermediate-mass stars (Kobulnicky & Zaritsky 1999). This result is in conflict with the spectral synthesis modeling by E96, which reproduced the SED of MS 1512−cB58 without a population of stars older than 1 Gyr. However, E96 only rule out an older population at the 2 σ confidence level, so we conclude that the older population of stars is likely.

3.3. Star Formation Rate

P2000 infer an observed (without correcting for the lensing magnification factor of 30) SFR = 2417 \( h_\odot^2 \) \( M_\odot \) yr\(^−1\) (\( q_0 = 0.1 \)) in MS 1512−cB58 from the 1500 Å continuum. This estimate included a factor of 7 correction for dust extinction [from an assumed \( E(B−V) = 0.24 \)].

Kennicutt (1983) relates the SFR to Hα luminosity, assuming a Salpeter initial mass function with an upper mass cutoff of 100 \( M_\odot \), by SFR(\( M yr^{-1} \)) = L(Hα)/11.2 × 10^{41} ergs s^{-1}. Kennicutt assumed 1.1 mag attenuation between Hα and radio fluxes, similar to that implied by our extinction measurement. We neglect the stellar absorption of Hα, which is likely to be only a 1–5 Å EW. We thus infer an (observed, lensing magnified) SFR = 620 ± 18 \( h_\odot^2 \) \( M_\odot \) yr\(^−1\) (\( q_0 = 0.1 \)). This rate is a factor of 2.18 higher than that measured by Bechtold et al. (1997), using narrowband imaging. This difference is the result of an atmospheric absorption trough at the wavelength of redshifted Hα that obscures approximately half the light. This absorption was not accounted for by Bechtold et al., who assumed \( z = 2.7233 \) rather than \( z = 2.729 \) for Hα (fortunately, their filter was wide enough to still detect the line).
While we measure a higher SFR from Hα than Bechtold et al. did, we do not resolve the question concerning the discrepancy with the rate inferred from the UV continuum, which was a factor of 3.9 higher. This discrepancy may be seen in the calculation of SFRs for local starbursts as well. Meurer et al. (1995) find UV fluxes that are 10 times the value predicted by Leitherer, Robert, & Heckman (1995) given measured Hα; recall that similar models of Leitherer et al. (1999; the updated Starburst99) were also used to calculate the SFR in MS 1512−cB58. Bechtold et al. speculate that a number of unlikely possibilities could logically account for the difference. We find no compelling resolution to the problem in the optical spectrum.

For vigorously star-forming galaxies with moderate to solar metallicity, the CO emission from the gas reservoir should be observable with existing ground-based radio telescopes. However, two attempts to measure the CO (3−2) line in MS 1512−cB58 have yielded only upper limits (Frayer et al. 1997; Nakanishi et al. 1997). The lack of detectable CO emission in MS 1512−cB58 may be the result of either a high CO-H2 conversion factor or a highly efficient formation of stars from the neutral hydrogen gas. Frayer et al. suggest that the star formation efficiency (SFE) of MS 1512−cB58 is a factor of 20 larger than in local starbursts. However, following the arguments in Frayer et al., if we take our measurement of metallicity, Z/Z⊙ = 0.32, and of SFR = 620 M⊙/yr−1, we would find only a factor of 1.7 increase in the SFE. Our assumptions would not address the high L(UV)/L(CO) ratio. However, we can bring the L(Hα)/L(CO) ratio closer to the local values (following Nakanishi et al. 1997).

4. CONCLUSIONS

While it is difficult to draw general conclusions from observations of one object, the rest-frame optical spectrum of MS 1512−cB58 affords us a preview of near-IR spectroscopy of LBGs. As expected (Seitz et al. 1998; P2000), cB58 does not appear to be a “protogalaxy” but rather a galaxy with significant metals produced in at least two phases. We find that the properties of MS 1512−cB58 are consistent with the interpretation of LBGs as progenitors of modern-day elliptical galaxies. Previous studies have also shown that the mass, SFR, and extinction of LBGs are appropriate in that context (e.g., P98). We have obtained the first measure of metal abundance in an LBG from the promising R53 method. The metallicity of 1/2 solar is in the range expected at this redshift from hierarchical models of elliptical galaxy evolution (Thomas 1999). Elliptical galaxies produce most of their stars, and hence metals, in the first z ~ 0.5 or 1 Gyr (Rocca-Volmerange & Fioc 2000), and therefore, at z ~ 3, they do not resemble low-redshift, extremely metal-poor galaxies but rather older low-z starbursts. Future LBG surveys with NIRSPEC will explore this connection (M. Pettini et al. 2000, in preparation). The ease with which our spectra were obtained (1.3 hr of telescope time) demonstrates the great potential for the observation of typical (K ≳ 20) LBGs with NIRSPEC or similar instruments.

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