A spectroscopically identified galaxy of probable redshift $z = 6.68$

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The detection and identification of distant galaxies is a prominent goal of observational cosmology because distant galaxies are seen as they were in the distant past and hence probe early galaxy formation, due to the cosmologically significant light travel time. We have sought to identify distant galaxies in very deep spectroscopy by combining a new spectrum extraction technique with photometric and spectroscopic analysis techniques. Here we report the identification of a galaxy of redshift $z = 6.68$, which is the most distant object ever identified. The spectrum of the galaxy is characterized by an abrupt discontinuity at wavelength $\lambda \approx 9300$ Å, which we interpret as the Ly$\alpha$ decrement (produced by intervening Hydrogen absorption), and by an emission line at wavelength $\lambda \approx 9334$, which we interpret as Ly$\alpha$. The galaxy is relatively bright, and the ultraviolet luminosity density contributed by the galaxy alone is almost ten times the value measured at $z \approx 3$.

At near-infrared wavelengths, where background sky light is the dominant source of noise, the Hubble Space Telescope (HST) using the Space Telescope Imaging Spectrograph (STIS) is more sensitive than the Keck telescope because (1) the sky is considerably fainter from space and (2) considerably higher spatial resolution is attained from space, thus admitting far less contaminating sky light. To exploit the unique sensitivity of STIS at near-infrared wavelengths, the Space Telescope Science Institute and the STIS instrument team at the Goddard Space Flight Center initiated the STIS Parallel Survey, in which deep STIS observations are obtained in parallel with other observations$^1$. We selected for analysis very deep observations acquired in slitless spectroscopy mode (which records the dispersed light of an entire field of view), because these observations are best suited for identifying distant galaxies.

The very deep observations were obtained by HST using STIS from 23 through 26 December, 1997 toward a region of sky flanking the Hubble Deep Field. Most observations consisted of a pair of images: a direct image taken using no filter and a dispersed image taken using the G750L grating. Additional observations consisted of only a direct image. The integration time of the direct images totaled 4.5 h over 82 exposures, and the integration time of the dispersed images totaled 13.5 h over 60 exposures.
We summed the direct and dispersed images using conventional image processing techniques. First, we reduced the images using standard pipeline software and applied corrections for flat-field variations and illumination pattern. Next, we registered each pair of images to a common origin, using pointing offsets determined from positions of bright stars in the direct images. Next, we measured the noise characteristics of the images, which are set by the background sky level and the readout noise. (The background sky level varies by as much as a factor of two between individual exposures.) Finally, we summed the direct images to form a summed direct image and summed the dispersed images to form a summed dispersed image, using optimal weights determined from the measured noise characteristics and rejecting deviant pixel values caused by cosmic ray events and hot pixels. The spatial resolution of the summed direct and dispersed images is FWHM $\approx 0.08$ arcsec, the $1\sigma$ single pixel detection threshold of the summed direct image is $\approx 26.2$ mag arcsec$^{-2}$, and the $1\sigma$ single pixel detection threshold of the summed dispersed image at $\lambda \approx 9800$ Å is $\approx 5.5 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ arcsec$^{-1}$.

We extracted one-dimensional spectra from the summed dispersed image using a new spectrum extraction technique. The extraction is made especially difficult because the image of the field is covered by light of faint galaxies, which when dispersed overlaps in a complicated way. To overcome this difficulty, we used the summed direct image to determine not only the exact locations but also the exact two-dimensional spatial profiles of the spectra on the summed dispersed image. These spatial profiles are crucial because (1) they provide the “weights” needed to optimally extract the spectra, and (2) they provide the models needed to deblend the overlapping spectra and determine the background sky level. First, we identified objects in the summed direct image, using the SExtractor program of Bertin & Arnouts$^2$. Roughly 250 objects were identified in the summed direct image. Next, we modeled each pixel of the summed dispersed image as a linear sum of contributions from (1) relevant portions of all overlapping neighboring objects and (2) background sky. The model parameters included roughly 250,000 “object” parameters (from roughly 1000 spectral pixels each of roughly 250 objects) and 5000 “sky” parameters (from roughly 1000 fourth-order polynomials). Finally, we minimized $\chi^2$ between the model and the data with respect to the model parameters to form one-dimensional spectra. (In practice, we imposed a condition of smoothness on the spectral variation of the sky in order to reduce the number of sky parameters. First, we smoothed the model of the sky by 10 pixels in the spectral direction, and we subtracted this model from the data. Next, we performed the extraction again, but this time with sky subtraction turned off. In this way we reduced the effective number of sky parameters from roughly 5000 to more like 500. We found by experimentation that this number of parameters is required to represent the spatial and spectral variations of the sky.)

We measured photometric redshifts from the one-dimensional spectra using a variation
of the photometric redshift technique described previously by Lanzetta, Yahil, & Fernández-Soto\textsuperscript{3,4} and Fernández-Soto, Lanzetta, & Yahil\textsuperscript{5}.

The results of the analysis are photometric redshift measurements of roughly 250 objects identified in the summed direct image. Here we focus on one particular galaxy identified by the analysis at a very high redshift, which we designate as galaxy A. The J2000 coordinates of galaxy A are $\alpha = 12 : 36 : 27.3$ and $\delta = +62 : 17 : 55.9$. Interpretation of the spectrum of galaxy A is especially straightforward because this galaxy does not overlap any other object in the dispersion direction. This means that in this case much of the machinery of the extraction technique described above (involving deblending overlapping spectra) does not actually come into play, although the technique is required in order to accurately determine the background sky level.

Figure 1 shows the direct image of galaxy A and its neighbors in the top panel. The dispersed image of galaxy A and its neighbors and a map of the detected emission lines are shown in the next two panels. The dispersed image of galaxy A with best-fit model spatial profiles of all objects but galaxy A subtracted is shown in the next panel. The one-dimensional spectrum of galaxy A, a redshifted spectrum of a moderate-redshift ($z = 4.421$) galaxy\textsuperscript{6}, and the one-dimensional spectrum of galaxy A cast into 325 Å bins together with the best-fit spectrophotometric template are shown in the next three panels. Figure 2 shows the redshift likelihood function of galaxy A. The spectrum of galaxy A is characterized by (1) an abrupt discontinuity at wavelength $\lambda \approx 9300$ Å, with detectable continuum emission at wavelengths $\lambda < 9300$ Å and an absence of detectable continuum emission at wavelengths $\lambda > 9300$ Å, and (2) an emission line at wavelength $\lambda = 9337 \pm 6$ Å. The redshift likelihood function of galaxy A is characterized by a maximum at redshift $z = 6.84$ and a local maximum at redshift $z = 6.66$, with the likelihood values of the primary and secondary maxima statistically indistinguishable. The energy flux of the emission line is $2.6 \pm 0.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$. We interpret the abrupt discontinuity as the Ly$\alpha$ decrement and the emission line as Ly$\alpha$, in which case the redshift of the galaxy determined from the emission line is $z = 6.68 \pm 0.005$.

Several lines of evidence support the validity of the spectrum extraction and the redshift identification:

First, the integrated energy flux measured from the direct image is in excellent agreement with the integrated energy flux measured from the dispersed image. The clear magnitude of galaxy A measured from the direct image is $AB(\text{clear}) = 27.67 \pm 0.09$, and the clear magnitude of galaxy A measured from the dispersed image is $AB(\text{clear}) = 27.72 \pm 0.29$ (which is obtained by integrating the product of the spectrum and the unfiltered spectrograph and system throughput). This demonstrates that the continuum emission detected at
wavelengths $\lambda \approx 9300 - 9950$ Å—which is crucial for establishing the redshift of galaxy A—is of exactly the amount required to explain the direct image. The clear magnitude of the emission line alone of galaxy A measured from the dispersed image is $AB(\text{clear}) = 29.15 \pm 0.24$. This demonstrates that the emission line alone cannot explain the direct image; rather, additional continuum emission must be present, namely the continuum emission detected at wavelengths $\lambda \approx 9300 - 9950$ Å. It is clearly unlikely that the analysis could have missed significant continuum emission at wavelengths $\lambda < 9300$ Å—where the spectrograph and system throughput is relatively high—and instead detected spurious emission (of exactly the amount required to explain the direct image) at wavelengths $\lambda > 9300$ Å.

Next, various arguments demonstrate the reality of other faint emission lines visible in the dispersed image. For example, we applied the SExtractor program to the smoothed dispersed image to objectively identify emission lines, setting the detection threshold such that nothing was detected in the negative of the image. The resulting segmentation map is shown in the third panel of Figure 1. Every emission line detected in the dispersed image by the SExtractor program can be attributed to a galaxy detected in the direct image. Specifically, the bottom-most emission lines arise in a very faint galaxy, designated galaxy B in Figure 1. The spectrum of galaxy B is relatively uncomplicated, because the galaxy just barely overlaps other galaxies above and below in the dispersion direction. Only very weak continuum emission is detected from the galaxy, but at least three emission lines are clearly evident in the dispersed image: an emission line to the right and below the emission line of galaxy A, another emission line in the same row just over 1/2 of the way from the left-hand edge of Figure 1, and another emission line in the same row off the right-hand edge of Figure 1. The identifications of the three emission lines are (left to right) Mg II $\lambda 2800$, He II $\lambda 3203$, and [O II] $\lambda 3727$ at a redshift of $z = 1.213$, which is substantiated by comparison with the ultraviolet spectrum of a starburst galaxy of Kinney et al. Furthermore, every emission line visible in Figure 1 (including another emission line below and to the right of the emission line of galaxy A and a “complex” of emission lines above and to the right of the emission line of galaxy A) is robust against image processing and cosmic ray rejection methods and is exactly coincident with the spatial profile of a galaxy detected in the direct image, as is evident from the bottom image of Figure 1.

Next, the abrupt discontinuity is consistent with interpretation as the Ly$\alpha$ decrement but inconsistent with the interpretation as other spectral breaks commonly observed in galaxy spectra. The average energy flux density measured from the dispersed image at wavelengths $\lambda = 7250 - 9250$ Å is $f_\nu(8250) = -0.01 \pm 0.04$ and at wavelengths $\lambda = 9400 - 9950$ Å is $f_\nu(9675) = 0.67 \pm 0.22$ μJy, which implies a decrement $1 - f_\nu(8250)/f_\nu(9675) = 1.01 \pm 0.06$. The corresponding $3\sigma$ lower limit to the break amplitude is 5.9, which exceeds by a significant factor the largest measured break amplitudes $\approx 2.6$ of early-type galaxies and $\approx 3$
of main-sequence stars (see Spinrad et al.\textsuperscript{8}).

Next, the statistically insignificant but suggestive “dip” in the spectrum of galaxy A at wavelengths between 9300 and 9500 Å matches qualitatively the expectation for stellar continuum radiation viewed through interstellar neutral Hydrogen, which is expected to imprint a damped Ly$\alpha$ absorption feature. Specifically, the redshifted spectrum of the moderate-redshift galaxy shows a corresponding dip, as is evident from comparison of the middle and top one-dimensional spectra of Figure 1. A similar feature is also present in the composite spectrum of 12 high-redshift ($z \approx 3$) galaxies presented by Lowenthal et al.\textsuperscript{9}

Finally, the redshift determined from the emission line is in excellent agreement with the redshift determined from the redshift likelihood function. Although difficult to quantify, the detection of an emission line at exactly the wavelength predicted by the photometric redshift measurement lends \textit{a posteriori} support to the redshift identification. In summary, the spectrum of galaxy A matches exactly the spectrum expected of a galaxy of redshift approaching $z = 7$ but is unlike the spectra expected of lower-redshift galaxies.

The most striking property of galaxy A is that it is relatively bright at wavelengths longward of Ly$\alpha$. Although galaxy A is exceedingly faint in any ordinary optical bandpass (due to very strong absorption by the Ly$\alpha$ forest), its continuum energy flux density at observed-frame wavelength $\lambda \approx 9800$ Å or rest-frame wavelength $\lambda \approx 1300$ Å is $f_\nu \approx 1 \mu$Jy, which is comparable to the continuum energy flux densities at similar rest-frame wavelengths of galaxies identified by Steidel and collaborators\textsuperscript{10} at redshifts $z \approx 3$. This corresponds to an unobscured star formation rate of $\approx 17 (147) \, h^{-2} \, M_\odot \, yr^{-1}$ for $q_0 = 0.5 \, (0.0)$, using the relationship between ultraviolet luminosity and star formation rate with a Salpeter initial mass function of Madau et al.\textsuperscript{11}. Taking the redshift range searched for very high redshift galaxies to extend from $z = 6$ to 7, the ultraviolet luminosity density contributed by galaxy A alone is almost ten times the value measured at $z \approx 3$. If the galaxy is typical of the very high redshift galaxy population, then apparently (1) very high redshift galaxies are luminous at rest-frame ultraviolet wavelengths and (2) the unobscured cosmic star formation rate may be substantially larger at $z \approx 7$ than at lower redshifts.

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ACKNOWLEDGEMENTS. We are grateful to H. Spinrad and to B. Woodgate, B. Hill, and the rest of the STIS instrument team for important discussions. This research was supported by NASA and NSF.

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Fig. 1.— Image and spectra of galaxy A and its neighbors. Top panel shows the direct image of galaxy A and its neighbors, with arrows pointing to galaxies A and B. Angular extent of the image is 51 arcsec wide by 2 arcsec high. The second panel shows the dispersed image of galaxy A and its neighbors, with arrows pointing to Lyα emission line of galaxy A. Pixel size is 4.882 Å in spectral direction and 0.05 arcsec in spatial direction, resolution is roughly two pixels (in both directions), and spectrum is boxcar smoothed by five pixels in spectral direction and two pixels in spatial direction. The third panel shows the map of the detected emission lines. (Note that the continua of the topmost bright objects have been broken up by the SExtractor program and are not individual emission lines.) The fourth panel shows the dispersed image with best-fit model spatial profiles of all objects but galaxy A subtracted. The fifth panel shows the one-dimensional spectrum of galaxy A. Pixel size is 5 Å, resolution is roughly two pixels, and spectrum is boxcar smoothed by three pixels. The sixth panel shows a redshifted (to $z = 6.68$) spectrum of a moderate-redshift ($z = 4.421$) galaxy. Bottom panel shows the one-dimensional spectrum of galaxy A cast into 325 Å bins together with best-fit spectrophotometric template spectrum. Vertical error bars indicate 1σ uncertainties and horizontal error bars indicate bin sizes. The images were recorded by a 1024 × 1024 CCD detector, which for the direct images was operated in unbinned mode (resulting in a 1024 × 1024 grid) and for the dispersed images was operated in 1 × 2 binned mode (resulting in a 1024 × 512 grid). The spatial scale of the image on the detector was 0.05 arcsec pixel$^{-1}$, which yielded a field of view of 51 × 51 arcsec$^2$. The telescope was displaced by several arcsec between each observation in order to reduce the effects of pixel-to-pixel sensitivity variations.

Fig. 2.— Redshift likelihood function of galaxy A. We measured photometric redshifts using a variation of the photometric redshift technique described previously. First, we adopted spectral templates of E/S0, Sbc, Scd, and Irr galaxies, including the effects of intrinsic and intervening neutral hydrogen absorption. (These spectral templates, which are described by Lanzetta, Yahil, & Fernández-Soto$^4$ and Fernández-Soto, Lanzetta, & Yahil$^5$, span rest-frame wavelengths $\lambda = 912 - 22,500$ Å.) Next, we constructed the “redshift likelihood functions” by calculating the likelihood of obtaining a measured spectrum given a modeled spectrum at an assumed redshift, maximizing with respect to galaxy spectral type and arbitrary flux normalization. Finally, we determined the maximum-likelihood photometric redshift measurements by maximizing the redshift likelihood functions with respect to redshift.
