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# *HUBBLE SPACE TELESCOPE* ULTRAVIOLET SPECTROSCOPY OF NGC 1741: A NEARBY TEMPLATE FOR DISTANT ENERGETIC STARBURSTS[1]

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## ABSTRACT

We have obtained a *Hubble Space Telescope* ultraviolet image and spectrum of the nearby Wolf-Rayet galaxy NGC 1741. The spatial morphology from the Faint Object Camera image is dominated by two main starburst centers, each being about 100 times as luminous as 30 Doradus. Both starburst centers are composed of several intense knots of recent star formation. A Goddard High Resolution Spectrograph spectrum of a portion of the southern starburst center is consistent with a population of young stars following a Salpeter IMF for masses above $\sim 15\ M_\odot$ (lower mass stars may also be present) and extending up to $\sim 100\ M_\odot$; about $10^4$ O-type stars are inferred from the UV luminosity.

Numerous strong interstellar lines are detected. Although not resolved, their strength suggests that they are formed in individual bubbles and shells with velocities up to a few hundred km $s^{-1}$. The red wing of the Ly$\alpha$ absorption profile indicates the presence of several neutral hydrogen components, one in our own Galaxy and the others at or close to the distance of NGC 1741. Overall, the stellar and interstellar line spectrum, as well as the continuum shape of NGC 1741, strongly resembles star-forming galaxies recently discovered at high redshift.

*Subject headings:* galaxies: evolution — galaxies: ISM — galaxies: starburst — galaxies: stellar content — ultraviolet: galaxies

## 1. INTRODUCTION

Starburst galaxies are a class of objects experiencing brief but intense episodes of star formation. Massive OB stars are dominant contributors to their ultraviolet and optical spectra in the first 10 Myr after the onset of the burst (see, e.g., Leitherer et al. 1996). Wolf-Rayet (W-R) galaxies are a subset of starburst galaxies that show *broad* stellar He II λ4686 emission in their spectra (Kunth & Sargent 1981; Conti 1991). Wolf-Rayet stars are the descendants of the most massive O stars, which show the products of nuclear burning at their surface due to mass loss and mixing processes (see, e.g., Abbott & Conti 1987). Because only the most massive stars evolve to form W-R stars, their presence in a starburst galaxy might suggest a stellar population with numerous high-mass stars present (Sargent & Filippenko 1991) *and/or* a rapid formation timescale (see, e.g., Vacca & Conti 1992, hereafter VC). The census of W-R stars in the Galaxy and in its OB associations indicates that they have progenitor masses above $\sim 40\ M_\odot$ (Conti et al. 1983; Humphreys, Nichols, & Massey 1985). Evolutionary synthesis models of stellar populations containing W-R stars (see, e.g., Meynet 1995) predict that about 3–6 Myr after the start of the burst, the most massive stars evolve into W-R objects, and the ratio of W-R to O stars increases dramatically. W-R galaxies therefore offer the unique opportunity to study a burst population the age of which is known a priori. The determination of the age $t$ and the initial mass function (IMF) of a starburst can in some cases be degenerate, i.e., the absence of $40\ M_\odot$ stars could imply either an upper mass limit $M_{up} < 40\ M_\odot$ or $t > 5$ Myr.

NGC 1741 (= Mrk 1089 = Arp 259) was first described as a W-R galaxy by Kunth & Schild (1986). It has a highly disturbed optical morphology with two starburst centers, possibly arising from a galaxy merger, most likely as a result of interaction with other members of Hickson Compact Group 31 (Hickson, Kindl, & Auman 1989; Rubin, Hunter, & Ford 1990). NGC 1741 is one of the most luminous W-R galaxies—optically and in the far-UV—in the catalog of Conti (1991): $M_B = -20.3$. VC obtained optical spectrophotometry of NGC 1741 and inferred the presence of about 700 W-R stars in the southern starburst center ("B" in their notation). We selected NGC 1741 as one of the targets for our ongoing program of *Hubble Space Telescope* (*HST*) observations of W-R galaxies. Ultraviolet imaging and spectroscopy have been obtained, confirming the presence of numerous OB stars in this galaxy. One purpose of this Letter is to draw attention to the spectral similarity between NGC 1741 and starburst galaxies recently discovered at high redshift, e.g., the "primeval galaxy candidate" cB58 (Yee et al. 1996), the star-forming galaxies at $z > 3$ (Steidel et al. 1996), and the "lensed" galaxy at $z = 2.5$ (Ebbels et al. 1996).

## 2. SPATIAL MORPHOLOGY

We obtained a pre-COSTAR ultraviolet image of NGC 1741 with the Faint Object Camera (FOC) on board *HST* on 1993 March 10. The observation was made in the f/96 config-

[1] Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA for NASA under contract NAS5-26555.

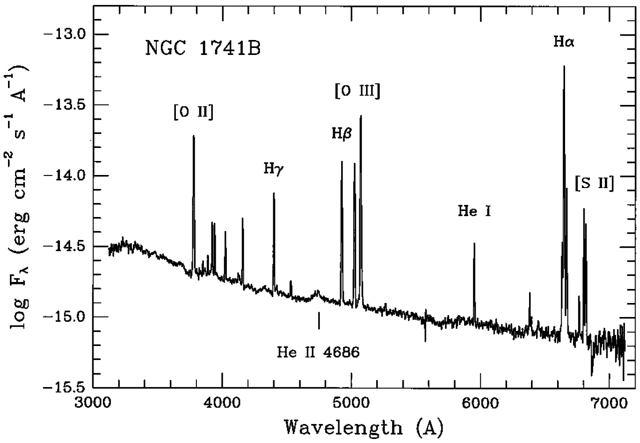


FIG. 2.—Long-slit (1″.5 wide) optical spectrum of NGC 1741B, taken at the 4 m telescope of CTIO and the 2D-Frutti detector (see VC for details). The wavelength scale is in the rest frame of NGC 1741 ($cz$ = 4000 km s$^{-1}$). Note the broad λ4686 emission due to W-R stars.

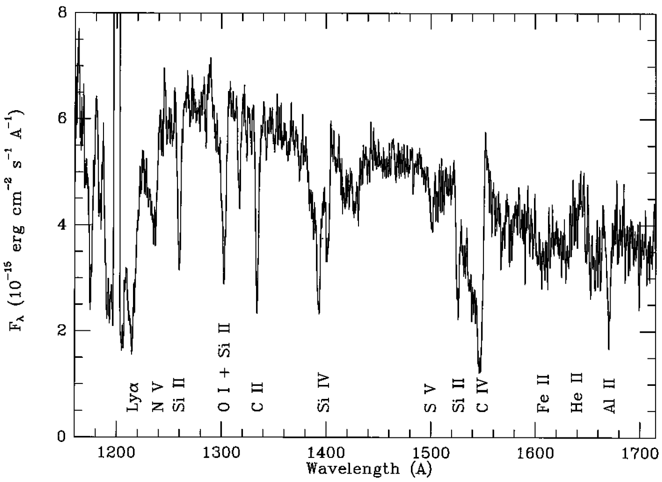


FIG. 3.—Observed GHRS spectrum of NGC 1741B1 through the 1″.74 LSA (see Fig. 1). The spectrum was obtained by merging two spectra centered on wavelength positions of 1320 Å and 1600 Å. Exposure times were 6100 s and 12200 s, respectively. A boxcar filter over 5 pixels has been applied, and the spectrum has been blueshifted into the rest frame of NGC 1741.

uration, in the "zoomed" format, with the F220W filter (effective wavelength of ∼2200 Å). The total exposure time was 996 s. The image format consists of 512 × 1024 pixels and has a field of view of ∼22″ × 22″. At NGC 1741's distance of 51 Mpc (VC; with $H_0$ = 75 km s$^{-1}$ Mpc$^{-1}$), this corresponds to a plate scale of 5.6 pc pixel$^{-1}$ or 250 pc arcsec$^{-1}$. Reduction and analysis of the image was done in the same manner as for the W-R galaxy NGC 4214 (Leitherer et al. 1996), and the reader is referred to that paper for details.

The FOC image is reproduced in Figure 1 (Plate L18). A preliminary discussion of this image has been given by Vacca (1994). Two star-forming centers are clearly resolved into numerous pointlike objects or starburst knots. The luminosity at 2200 Å of the *individual* knots ranges beyond an order of magnitude larger than that of 30 Doradus. (We will discuss the photometry along with recently acquired WFPC2 optical images of NGC 1741 in a subsequent paper.) The northeastern center (J2000 coordinates 5$^h$01$^m$37$^s$.76, −4°15′29″.0 and extending over about 2″) corresponds to region "A" of VC. The southwestern center, overfilling the Goddard High Resolution Spectrograph (GHRS) aperture, is region "B" of VC and is responsible for the W-R features observed in the optical spectrum.

## 3. OPTICAL AND ULTRAVIOLET SPECTRA

An optical spectrum of NGC 1741B had been obtained and discussed by VC. Because the spectrum was not shown in that paper, it is included here for completeness (Fig. 2). The long-slit spectrum (width 1″.5, P.A. 17°.5) includes all the flux measured by the GHRS aperture, plus some outside. The optical spectrum is dominated by strong nebular emission lines, as expected from the presence of hot, massive stars. The number of ionizing photons in the Lyman continuum is $2 \times 10^{53}$ s$^{-1}$ (VC). This is more than 2 orders of magnitude higher than observed in 30 Doradus. VC used the λ4363 [O III] line to derive an oxygen abundance of O/H = $2 \times 10^{-4}$ ($\frac{1}{4}$ $Z_\odot$), lower than the 30 Doradus value. The broad emission line at λ4686 is due to W-R stars. It is the only directly observed line from hot, massive stars in the optical range in this galaxy. Weak absorption lines are recognizable at the wavelength of the higher Balmer series and at the Ca K line, which suggests that stars of spectral type late B and cooler contribute to the optical continuum as well.

The GHRS observations were executed on 1995 August 17. NGC 1741B was acquired on Side-2 with a 5 by 5 spiral search and centered into the 1″.74 Large Science Aperture (LSA). Then a side-switch was performed for observations at two wavelength settings with grating G140L, one centered on 1320 Å and the other on 1600 Å. Wavelength calibrations were obtained for both grating positions. The reduced spectrum is shown in Figure 3. A more detailed data analysis will be given subsequently. We will refer to the portion of NGC 1741B enclosed within the GRHS aperature (Fig. 1) as NGC 1741B1.

The ultraviolet spectrum of NGC 1741B1 is similar to knots in other starburst galaxies observed with *HST*, such as NGC 4214 (Leitherer et al. 1996). However, no starburst galaxy has been observed before in the ultraviolet at a spectral resolution and signal-to-noise ratio comparable to our data presented here. The geocoronal Lyα was measured at 1216.1 Å, consistent with the expected wavelength accuracy of this grating/aperture combination. The narrow interstellar lines of NGC 1741B1 show a small blueshift of about 1 Å in its rest frame (defined from the optical nebular features). This blueshift is also present in the Galactic foreground interstellar lines. Most likely, this offset results from a nonuniform light distribution of NGC 1741B1 in the LSA, which is projected on eight science diodes of the detector (Fig. 1). Lyα has a FWHM of 4.9 Å, as expected for a uniform light source filling the LSA completely. The theoretical FWHM of a spectral line due to a point source is 0.7 Å. All interstellar lines have widths ∼3 Å. We interpret this as a result of the complex structure of NGC 1741B1 partially filling the LSA, rather than having resolved the interstellar lines.

## 4. STELLAR POPULATION AND INTERSTELLAR MEDIUM

The ultraviolet spectral morphology of starbursts and the spectral synthesis methods of analyses are described in detail in Leitherer, Robert, & Heckman (1995) and Leitherer et al. (1996). The most conspicuous *stellar* lines in NGC 1741B1 are C IV λ1550, Si IV λ1400, N V λ1240, and He II λ1640. These lines have broad absorptions and/or emissions because of their

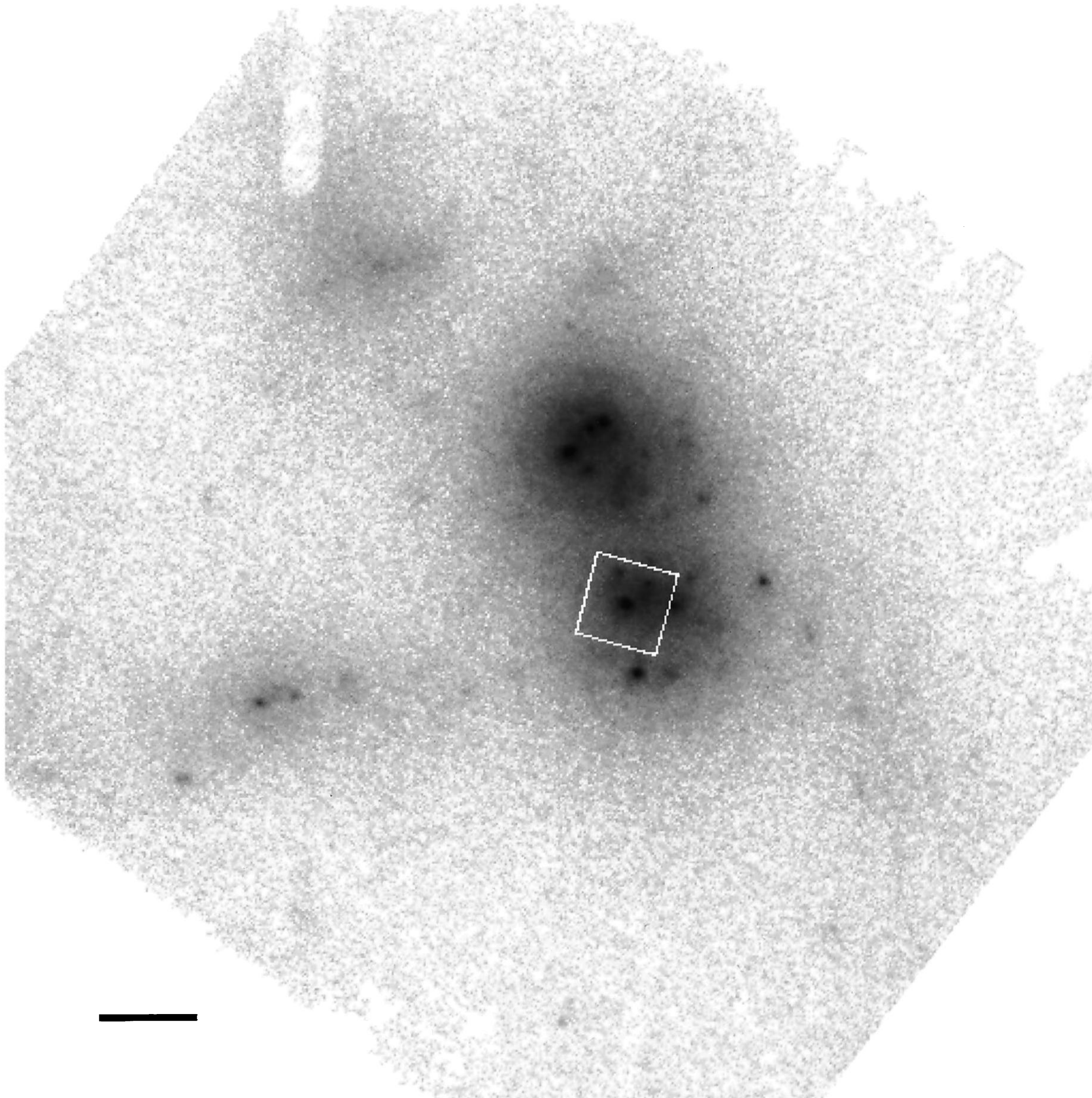

FIG. 1.—Ultraviolet image of NGC 1741 observed with the FOC. The image is ~22″ × 22″; the plate scale is 0″.022497 pixel$^{-1}$. North is up, and east to the left. NGC 1741A is the upper starburst region; NGC 1741B, the lower. The horizontal bar in the lower left-hand corner is 2″ long. The square indicates the location of the GHRS 1″.74 entrance aperture, which was used for the ultraviolet spectrum of NGC 1741B1.

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origin in stellar winds from hot stars. The C IV λ1550 and Si IV λ1400 profiles indicate a standard IMF with a Salpeter slope ($\alpha = 2.35$) in the mass range 15–100 $M_\odot$ (the likely presence of lower mass stars cannot be confirmed from these UV data). The most massive stars *currently* present in the burst are at least above 60 $M_\odot$ and probably around 100 $M_\odot$. This result is similar to what is found in other starburst galaxies (Robert, Leitherer, & Heckman 1993; Leitherer et al. 1996). The blue edge of Si IV λ1400 requires a population of evolved O supergiants, which appear between 3 and 6 Myr after the onset of the burst if there is no ongoing star formation. If star formation continues, the Si IV profile is consistent with any age above 3 Myr. The existence of W-R stars suggests an age in the same range—independent from the line profile–fitting method. Unfortunately, the observed N V λ1240 emission is severely blended with Galactic S II/Si II foreground absorption (see below). The best fit for the age of the starburst is 4–5 Myr.

The inferred monochromatic luminosity of NGC 1741B1 at 1500 Å is $L_{1500} = 5.6 \times 10^{39}$ ergs s$^{-1}$ Å$^{-1}$ [$D = 51$ Mpc; $E(B-V) = 0.15$ mag; see below]. This value implies a number of ionizing stars roughly consistent with the Lyman-continuum photon number of $2 \times 10^{53}$ s$^{-1}$ from NGC 1741B (which is larger in area). The GHRS aperture of NGC 1741 contains one bright starburst knot (giant H II region), some fainter knots, and some diffuse background (Fig. 1). Part of the diffuse background may be an artifact of the pre-COSTAR FOC image. Note that the presence of discrete *knots* that dominate the UV image (Fig. 1) strongly suggests that the most recent star formation process took place in *bursts* (see also Conti & Vacca 1994).

The monochromatic luminosity of NGC 1741B1 at λ1500 = Å corresponds to $\sim 10^4$ O-type stars (following Conti 1996). We measure a luminosity in the broad He II emission line at λ1640 = Å of $L_{\rm He\,II\,1640} = 3 \times 10^{39}$ ergs s$^{-1}$. As calibrated by Conti (1996), this corresponds to about 500 WN-type stars. These star numbers are in reasonable agreement with the values of $1.7 \times 10^4$ O types and 710 WN types inferred from the optical spectrum of the larger NGC 1741B optical region by VC.

The *optical* continuum of NGC 1741B is several times stronger than predicted by any model that could reproduce the ultraviolet. We interpret this as being partly due to knots other than B1 in the region (Fig. 1) and also as an indication of an older underlying population having an age of at least a few tens of Myr (our raw WFPC2 optical images indicate such a background). This population can account for the observed Balmer-line absorptions and for the low H$\beta$ equivalent width of 80 Å. Model predictions for $W$(H$\beta$) are quite robust (see Leitherer & Heckman 1995) but fail to agree with the observations by a factor of about 3 in the case of NGC 1741B (data from VC).

We observe two systems of interstellar lines in NGC 1741B1: one originating there, and the other one within our Galaxy. The strongest interstellar lines are in NGC 1741B1: Si II λ1260, O I/Si II λ1303, C II λ1335, Si II λ1526, and Al II λ1670, as well as the interstellar components in C IV λ1550, Si IV λ1400, and N V λ1240. Note that C II λ1335 could also have a stellar contribution from early-B supergiants. There are weaker Galactic lines (blueshifted by 4000 km s$^{-1}$ in Fig. 3), most notably Si II λ1260 (blended with the emission component of N V λ1240) and C II λ1335. Average equivalent widths of unblended interstellar lines in NGC 1741B1 are around 2 Å, which is fairly typical for starburst galaxies (York et al. 1990). This value can be used to constrain the kinematics of the interstellar medium. (For reasons given above, the measured line width is probably not a good indicator.) At 1500 Å, this corresponds to a velocity dispersion $\sigma > 100$ km s$^{-1}$ if the broadening is due to a single, virialized gravitational motion, and the implied gravitational masses would be in excess of $10^{11}$ $M_\odot$, too high for an irregular galaxy such as NGC 1741. Alternatively, the observed equivalent width could be the result of many unresolved, unsaturated, narrow interstellar lines over a velocity range of a few hundred km s$^{-1}$. Shells and bubbles around individual starbursts or even a large-scale outflow of the ISM in NGC 1741B1 could be responsible. A similar suggestion for the W-R galaxy NGC 4214 has been made by Leitherer et al. (1996) in order to explain the anomalous strength of the interstellar lines in that galaxy in comparison with individual Galactic stars.

The continuum of NGC 1741B1 is only mildly reddened by dust. Comparison with theoretical models using the ultraviolet continuum fitting method of Leitherer et al. (1996) suggests a total $E(B-V) = 0.15$ mag. The average Galactic foreground neutral hydrogen column density at the position of NGC 1741 is $4 \times 10^{20}$ cm$^{-2}$ (Stark et al. 1992), which suggests a foreground reddening of 0.1 mag, which leaves 0.05 mag for internal reddening. We dereddened the continuum using $E(B-V) = 0.1$ mag and a Galactic law, and 0.05 mag with the extragalactic extinction law of Kinney et al. (1994).

The extinction-corrected continuum shows a pronounced turnover shortward of 1260 Å—despite the rising continuum of massive stars. The turnover is due to the wing of a Ly$\alpha$ absorption profile, due partly to Galactic absorption, and also neutral H in NGC 1741 itself. Test calculations using line profile–fitting demonstrate that the red Ly$\alpha$ wing can be reproduced by a Galactic neutral hydrogen column density of the order of $10^{21}$ cm$^{-2}$ and (possibly) three Ly$\alpha$ components at or close to the redshift of NGC 1741B1 with a total column density of several times $10^{19}$ cm$^{-2}$. The blue Lyman-$\alpha$ wing has a strong blend due to N I λ1200, and a weaker feature of Si III λ1206, and thus cannot be easily modeled. The Ly$\alpha$ column density near NGC 1741B1 is typical of strong "Lyman limit" lines along lines of sight to QSOs.

## 5. IMPLICATIONS FOR STAR-FORMING GALAXIES AT HIGH REDSHIFT

NGC 1741B1 is made up of $\sim 10^4$ O-type stars concentrated in one strong star-forming knot and some weaker knots plus background, most of which collectively originated less than 10 Myr ago. Although the hot stars dominate the energetics of the UV, and the nebular lines (Fig. 2) that dominate the optical are a direct result of thermal excitation of the interstellar gas, the Ly$\alpha$ line is in *absorption*. The lack of Ly$\alpha$ emission is probably due to multiple scattering by dust within NGC 1741. This result has been noted previously in other starburst systems (see, e.g., Hartmann et al. 1988). NGC 1741 is clearly not a "*primeval galaxy*," as it shows evidence of an underlying older population of stars.

Nevertheless, the ultraviolet spectrum of NGC 1741B1 (Fig. 3) is strikingly similar to that of the highly redshifted ($z = 2.72$) "primeval galaxy candidate" cB58 of Yee et al. (1996), to the "star-forming galaxies" at redshifts $z > 3$ of Steidel et al. (1996), and to the "lensed" galaxy at $z = 2.5$ (Ebbels et al. 1996). The agreement in spectral morphology extends both from the perspective of the P Cygni wind profiles of Si IV and C IV, and from the strong interstellar lines of O I, C II, Si II, and Al II. The former lines clearly indicate the presence of O-type stars, for which we have modeled a burst age of a few Myr in NGC 1741B1. Yee et al. (1996) derive a slightly older age in their burst model, but they also suggest that "continuous" star formation may be operating for a somewhat longer time in their galaxy. The photometry and spectroscopy of cB58 are currently inconclusive regarding this distinction. The galaxies of Steidel et al. (1996) clearly have young stars present from their UV spectra, but these authors claim the spectral energy distribution suggests "continuous" star formation operates in their systems.

The interstellar lines in cB58 are about a factor of 2 stronger in equivalent width, whereas those in the Steidel et al. (1996) galaxies are similar to NGC 1741B1. We have noted above that the equivalent widths of the interstellar lines in NGC 1741B1 are *likely* dominated by nonthermal processes and thus cannot be safely used for mass determinations. This *might* be a consideration to be aware of in more distant galaxies.

A luminosity comparison of NGC 1741B1 with the star-forming galaxies at $z > 3$ is instructive: Steidel et al. (1996) quote $L_{1500} = 10^{41}\ h_{50}^{-2}$ ergs s$^{-1}$ Å$^{-1}$ for $q_0 = 0.5$, and a little greater for smaller $q_0$. The value for NGC 1741B1 is $L_{1500} \sim 1.2 \times 10^{40}$ *in the same units*—about 10 times fainter. In our starburst region, the $L_{1500}$ comes from a bright starburst *knot* and some fainter contributors (see Fig. 1). These represent an appreciable fraction of the *optical* light of the starburst region, where contributions from older stars are also present. The "lensed" galaxy is similar in luminosity to the objects of Steidel et al. (1996). The Yee et al. (1996) galaxy is a factor of 10 (to 100 with an uncertain extinction correction) brighter than the $z > 3$ galaxies. Although NGC 1741B1 is only a miniature version of the starburst phenomena exhibited by these more distant systems, its *UV spectrum* closely resembles them. We offer a very speculative question: could the *burst mode* of star formation we find in NGC 1741B1 have application to the very earliest stages of galaxy formation, or are they necessarily completely different? High spatial resolution imaging of the very distant galaxies would be helpful in addressing their spatial morphology. Is the star formation process "galaxy wide," or is it concentrated in "discrete regions"? Similarly, is the process relatively "continuous," or is it "burstlike," in the very earliest galaxy formation episodes?

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