UPDAted models for the creation of a low-z QSO absorber by a dwarf galaxy wind*

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abstract

We present new GALEX images and optical spectroscopy of J1229+02, a dwarf post-starburst galaxy located 81 kpc from the 1585 km s\(^{-1}\) absorber in the 3C 273 sight line. The absence of H\(\alpha\) emission and the faint GALEX UV fluxes confirm that the galaxy’s recent star formation rate is \(<10^{-3} M_{\odot} \text{yr}^{-1}\). Absorption-line strengths and the UV–optical SED give similar estimates of the acceptable model parameters for its youngest stellar population where \(f_{\text{e}} < 60\%\) of its total stars (by mass) formed in a burst \(t_{\text{e}} = 0.7–3.4\) Gyr ago with a stellar metallicity of \(-1.7 < [\text{Fe/H}] < +0.2\); we also estimate the stellar mass of J1229+02 to be \(7.3 < \log (M_{\text{e}}/M_{\odot}) < 7.8\). Our previous study of J1229+02 found that a supernova-driven wind was capable of expelling all of the gas from the galaxy (none is observed today) and could by itself plausibly create the nearby absorber. But, using new data, we find a significantly higher galaxy/absorber velocity difference, a younger starburst age, and a smaller starburst mass than previously reported. Simple energy-conserving wind models for J1229+02 using fiducial values of \(f_{\text{e}} \sim 0.1, t_{\text{e}} \sim 2\) Gyr, and \(\log (M_{\text{e}}/M_{\odot}) \sim 7.5\) allow us to conclude that the galaxy alone cannot produce the observed QSO absorber; i.e., any putative ejecta must interact with ambient gas from outside J1229+02. Because J1229+02 is located in the southern extension of the Virgo cluster ample potential sources of this ambient gas exist. Based on the two nearest examples of strong metal-line absorbers discovered serendipitously (the current one and the 1700 km s\(^{-1}\) metal-line absorber in the nearby Q1230+0115 sight line), we conclude that absorbers with \(10^{14} < N_{\text{HI}} < 10^{16}\text{ cm}^{-2}\) at impact parameters \(\sim 1 R_{\text{vir}}\) are likely intergalactic systems and cannot be identified unambiguously as the circumgalactic material of any one individual galaxy.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: halos – intergalactic medium – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

The low-redshift “Ly\(\alpha\) forest” was discovered by Morris et al. (1991) and Bahcall et al. (1991) in the ultraviolet spectrum of 3C 273 using the first generation spectrographs on the Hubble Space Telescope (HST). Two specific Ly\(\alpha\) + metal-line absorbers\(^2\) at \(z = 1015\) and 1585 km s\(^{-1}\) in the spectrum of 3C 273 attracted significant early and continuing interest (Morris et al. 1991; Weymann et al. 1995; Sembach et al. 2001; Tripp et al. 2002; Rosenberg et al. 2003) due to their high column density (\(\log N_{\text{HI}} = 14.41\) and \(15.85\text{ cm}^{-2}\), respectively) and proximity to Earth.

Extensive galaxy surveys in the region around 3C 273 (Morris et al. 1991, 1993) and other HST-observed targets (e.g., Tripp et al. 1998; Prochaska et al. 2004, 2011; Chen & Mulchaey 2009; Johnson et al. 2013) have found that, in general, the association between absorbers and galaxies is rather loose. Most low column density \((\log N_{\text{HI}} < 14.0\text{ cm}^{-2})\) absorbers are associated not with individual galaxies but rather with large-scale “filaments” of galaxies. A small percentage (~20\%) of these low column density absorbers are even found in galaxy voids (Stokoe et al. 2007).

At higher H\(\text{I}\) column densities, Ly\(\alpha\) absorbers are routinely found associated with individual galaxies or groups of galaxies (Stocke et al. 2013, 2014). At \(\log N_{\text{HI}} \geq 14.5\text{ cm}^{-2}\), approximately 50\% of Ly\(\alpha\) absorbers are projected within the virial radius of a galaxy, almost always a star-forming galaxy (Stocke et al. 2013; Tumlinson et al. 2011; Thom et al. 2012). The percentage of absorption systems closely associated with galaxies increases with column density. While these associations are usually with \(L \geq 0.1 L^\ast\) galaxies, a smaller proportion are associated with dwarfs (Stocke et al. 2013). For Lyman-limit systems \((\log N_{\text{HI}} > 17.2\text{ cm}^{-2})\) virtually all absorber systems are found within \(\approx 100\text{ kpc}\) of a \(L \geq 0.1 L^\ast\) galaxy (Steidel et al. 1993). At the highest column densities \((\log N_{\text{HI}} > 20.3\text{ cm}^{-2})\), the damped Ly\(\alpha\) absorbers are associated with galaxies with a variety of luminosities (Wolfe et al. 2005; Zwaan et al. 2005; Rosenberg & Schneider 2003) and are thought to arise primarily in the thick gaseous disks of galaxies (Wolfe et al. 2005) but some of these systems may arise in tidal debris between galaxies.

Given the previous results on absorber-galaxy associations and the relatively high column density of the 1585 km s\(^{-1}\) absorber, we might expect to find a nearby galaxy for which the 3C 273 sight line is projected within its virial radius. Indeed, a post-starburst dwarf spheroidal galaxy (SDSS J122950.57 + 020153.7, J1229+02 hereafter) was discovered only 71 kpc away on the sky (Morris et al. 1993). Not only is J1229+02 the closest galaxy to the absorber but also the post-starburst spectrum is unusual for such a small galaxy \((M_B = -16)\). Stocke et al. (2004), Paper 1 hereafter, showed that a wind

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1 Hubble fellow.

2 The 1015 km s\(^{-1}\) absorber will not be discussed further in this paper; see Stokoe et al. (2013, 2014) and Savage et al. (2014) for new analysis of this absorber.
emanating from this dwarf due to a recent starburst is plausibly sufficient to produce the 1585 km s⁻¹ ¹₂O absorption. This putative wind also appears to have left the system without any detectable gas (Paper 1; van Gorkom et al. 1993), which suggests that J1229+02 will simply fade over the next few billion years to eventually attain a luminosity comparable to the most luminous Local Group dwarfs unless it accretes new gas to fuel subsequent star formation episodes. This scenario is reminiscent of galaxy evolution for the “faint blue galaxy” population proposed by Babul & Rees (1992).

This hypothesis was proposed to explain the plethora of very faint, blue galaxies found by deep CCD imaging surveys (B ~ 24–27; Tyson 1988). A star-bursting dwarf at M_B ~ −18 would have B ~ 24 at z ~ 0.5 and very blue colors. But if a supernova-driven wind cleared almost all of the gas from this small galaxy, then it would form no more stars and simply fade. Eventually such a galaxy could reach the very low luminosity of a Local Group dwarf (M_B ≥ −14) if there was no new star formation. Without a significant fading of the bulk of the very numerous faint, blue galaxy population at z ≥ 0.5, it is not possible to understand their absence in the current epoch. J1229+02 is the best current example of a Babul & Rees object in the process of fading.

If the galaxy wind interpretation for J1229+02 is correct, this absorber/galaxy pair may also be the best example of a dwarf galaxy wind producing a metal-enriched absorber due to gas that is escaping into the intergalactic medium (IGM). The absorber metallicity of only 6% solar roughly matches the metallicity obtained for J1229+02 using Lick indices ([Fe/H] = −1.0 ± 0.5; see Paper 1). For a single-burst model (Poggianti et al. 2001; Bruzual & Charlot 1993; Worthy 1994) in which virtually all of the luminosity of the galaxy was created, an age of 3.5 ± 1.5 Gyr is obtained for the starburst. If a significant number of older stars is present in the galaxy, then a smaller, younger starburst is required to obtain the observed absorption line strengths, which roughly match the spectral signature of late-A and early-F type main sequence stars. An overabundance of [Si/C] suggests an absorber origin due to recent Type II supernovae explosions (past few billion years; Tripp et al. 2002). The metallicity values and silicon overabundance support the association of the absorber and J1229+02.

Based on the single-burst model for J1229+02, the galaxy/absorber radial velocity difference and the luminosity-derived galaxy mass, Paper 1 constructed a simple model confirming that the 1585 km s⁻¹ absorber could have been produced by a supernova-powered wind from J1229+02, even in the case where the mass outflow from the galaxy is entirely isotropic. However, there were a few uncertainties involved in this modeling, including whether the galaxy/absorber radial velocity difference reported in Paper 1 was correct and whether a single-burst model is viable given the very high star formation rate (SFR) required (~1 M_☉ yr⁻¹; Paper 1).

However, even if these modeling uncertainties can be resolved we are left with the fundamental ambiguity of associating the 1585 km s⁻¹ absorber with any individual galaxy. J1229+02 is located in the southern extension of the Virgo cluster where there are many galaxies at similar velocities (see also Figure 2 of Stocke et al. 2014 for the distribution of galaxies near 3C 273 at Virgo velocities). Given the faint completeness limits of the Sloan Digital Sky Survey (SDSS) and pointed surveys in the region (e.g., Morris et al. 1993), there is little doubt that J1229+02 is the closest galaxy (~1 R_vir in projection; Stocke et al. 2013) to the 3C 273 sight line with a velocity near that of the 1585 km s⁻¹ absorber. However, due to its higher luminosity NGC 4409 is a comparable number of virial radii from the 3C 273 sight line (~1.5 R_vir in projection, although low-ionization absorbers like the one we study are typically associated with galaxies located within ~0.6 R_vir; Stocke et al. 2013) despite having a projected physical distance ~3.5 times larger than that of J1229+02 (Stocke et al. 2013). The recession velocity of NGC 4409 is also closer to the absorber velocity than that of J1229+02. In Figure 1 we show the locations of 3C 273, NGC 4409, and J1229+02 in the GALEX tile GI4_012003, as well as zoomed-in SDSS and GALEX views of J1229+02. Thus, the density of galaxies in this part of the sky is such that we cannot unambiguously associate the 1585 km s⁻¹ absorber in the 3C 273 sight line with any individual galaxy, and an association with larger-scale group/cluster gas is also a distinct possibility (Yoon et al. 2012; Stocke et al. 2014).

Nevertheless, the star formation history of J1229+02 and its connection to the Babul & Rees (1992) picture of fading blue galaxies make it an interesting object to study in its own right. In this paper we present new high signal-to-noise (S/N) optical spectroscopy (Section 2) and new Galaxy Evolution Explorer (GALEX) images (Section 3) of J1229+02. The revised recession velocity of J1229+02 increases the velocity difference between the galaxy and the absorber, increasing the energy required to eject the absorber to its observed distance from the dwarf if the absorber originates in a galaxy wind. Despite the increased energy requirements, we show in Section 4 that a simple model still fits this absorber/galaxy system and argue that this tiny dwarf could plausibly create the strong nearby absorber. Our results are summarized in Section 5.

2. OPTICAL SPECTROSCOPY OF J1229+02

New high-resolution optical spectra of J1229+02 were obtained with the Dual Imaging Spectrograph (DIS) at the Apache Point Observatory (APO) 3.5 m telescope to better constrain the lack of Hα emission and refine the galaxy’s recession velocity, which SDSS (1775 ± 12 km s⁻¹) found to be discrepant from the value in Paper 1 (1635 ± 50 km s⁻¹). Contamination of the galaxy’s Ca II K by solar Ca II H absorption was suspected in the Las Campanas 2.6 m spectrum used in Paper 1 due to the presence of moonlight during the observation; therefore, we were careful to observe J1229+02 only during dark time at APO.

J1229+02 was observed for 3 hours on 2011 May 05 with the R1200 grating and 2 hours on 2011 May 25 with the B1200 and R1200 gratings. A 1° wide slit was used on both nights and both gratings have dispersions of ~0.6 arcsec pix⁻¹, corresponding to velocity resolutions of ~70 km s⁻¹ and ~100 km s⁻¹ at the observed positions of Hα and Hβ, respectively. We observed J1229+02 with the highest resolution gratings for which it was feasible to maximize our ability to resolve Hα emission, but the resulting spectra only cover wavelength regions of 5800–6900 Å with S/N ~ 10 pix⁻¹ and 4150–5400 Å with S/N ~ 5 pix⁻¹. Thus, the SDSS spectrum is superior to ours in terms of both wavelength coverage and S/N and we defer to it in our analysis in situations where these properties are advantageous.
Figure 2 shows the APO/DIS spectrum compared to the lower resolution (~150 km s^{-1}) SDSS spectrum in the regions of H\alpha and H\beta absorption from J1229+02. The QSO absorber velocity of 1585 km s^{-1} and the SDSS-derived galaxy velocity of 1775 km s^{-1} are indicated by the dashed vertical lines. In the APO/DIS spectrum, one pixel corresponds to ~25 km s^{-1} at H\alpha, and ~40 km s^{-1} at H\beta.

Figure 2. High-resolution optical spectrum of J1229+02 from APO/DIS (black) compared to the SDSS spectrum (blue) in the regions of H\alpha and H\beta absorption from J1229+02. The QSO absorber velocity of 1585 km s^{-1} and the SDSS-derived galaxy velocity of 1775 km s^{-1} are indicated by the dashed vertical lines. In the APO/DIS spectrum, one pixel corresponds to ~25 km s^{-1} at H\alpha, and ~40 km s^{-1} at H\beta.

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

3. GALEX IMAGING OF J1229+02

The absorption-line analysis presented in the preceding section and in Paper 1 is one method of attempting to constrain the age and metallicity of a galaxy. Another is to examine the galaxy’s broadband spectral energy distribution (SED) and model it as the superposition of one or more simple stellar populations with single-valued ages and metallicities. This endeavor is made easier if the galaxy to be modeled is observed in its rest-frame ultraviolet where there can be a large difference between the luminosity of a population of young and old stars.

To this end, J1229+02 was observed by GALEX for 1.66 ksec in GI Cycle 4 as part of tile GI4_033001 (PI: B. Keeney). The goal of these observations was to measure the galaxy velocity are indicated by the dashed vertical lines in Figure 2.

Estimates of the galaxy’s age and metallicity in Paper 1 were determined from an analysis of its Lick indices, particularly the H\alpha and H\beta indices for age sensitivity and the \langle Fe \rangle and Mg_2 indices for metallicity sensitivity (Poggianti et al. 2001). In the meantime, considerable effort has gone into recalibrating the Lick indices at SDSS resolution (e.g., Kauffmann et al. 2003; Eisenstein et al. 2003; Bruzual & Charlot 2003; Schiavon 2007; Graves & Schiavon 2008; Franchini et al. 2010, 2011) so their power can be brought to bear on the vast array of SDSS spectra. We have used the EZ_Ages software of Graves & Schiavon (2008) to measure Lick indices from the SDSS spectrum of J1229+02 and calculate its age and metallicity. This analysis finds an age of 2.1^{+1.0}_{-0.5} Gyr and a metallicity of [Fe/H] = -1.2^{+0.5}_{-0.5}, which despite the lack of a formal upper bound on metallicity is nonetheless broadly consistent with the age (3.5 \pm 1.5 Gyr) and metallicity ([Fe/H] = -1.0 \pm 0.5) of Paper 1.

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

Figure 1. SDSS and GALEX images of J1229+02. At left we show GALEX tile GI4_012003 (1''2 diameter), which we use for UV photometry in Section 3. A circle indicates the position of 3C 273 and boxes indicate the positions of NGC 4409 (big box) and J1229+02 (small box). At right we show zoomed-in color (~2' \times 2' FOV) images centered on J1229+02 from SDSS (top) and GALEX (bottom).

(A color version of this figure is available in the online journal.)
NUV and FUV magnitudes of J1229+02 and use them to model its star formation history. Fortuitously, additional GALEX images of the galaxy were acquired in the same cycle as part of tile G4_012003 (PI: K. Sembach). This tile is much deeper than the one obtained as part of our program (FUV exposure time of ~30 ksec and NUV exposure time of ~50 ksec), so we use it for all subsequent analysis in this paper.

GALEX images in the FUV and NUV channels simultaneously with spatial resolutions of 4.2' and 5.3', respectively, and a circular field of view 1.2' in diameter (Morrissey et al. 2007). A sophisticated data reduction pipeline is employed to reconstruct images from the raw telemetry; many details of this pipeline can be found in Morrissey et al. (2007), but we briefly list its salient features here. Photon positions are corrected for various instrumental effects and turned into raw-count images, then divided by a relative response image that incorporates the effective exposure time of each pixel to create a flux-calibrated intensity image. The background in the intensity image is estimated using a custom threshold image and then subtracted. Finally, SExtractor (Bertin & Arnouts 1996) is used to determine source positions and photometry in the NUV and FUV images and the NUV and FUV source catalogs are combined to form a merged catalog of source positions, fluxes, and magnitudes.

As evidenced by the zoomed-in image in the bottom right corner of Figure 1, J1229+02 has several faint neighbors within ~1' in the deep GALEX exposures so care is needed when determining its magnitude. Despite its low redshift, J1229+02 is small enough on the sky to be only marginally resolved by GALEX (90% of its r-band flux is contained within a 10'' radius; see Figure 1). Thus, we effectively treat J1229+02 as a point source in the GALEX images and use aperture magnitudes (specifically, the “APER_4” magnitudes with a radius of 8 pix = 12'') chosen to have a size that roughly corresponds to the size of the galaxy in the SDSS images. This procedure yields an NUV magnitude for J1229+02 of 21.11 ± 0.01 and an FUV magnitude of 22.30 ± 0.03. For comparison, the NUV and FUV magnitudes of J1229+02 derived from our notably shallower tile are 21.08 ± 0.06 and 22.43 ± 0.17, respectively. We also note that the UV surface brightness profile of J1229+02 is quite smooth, consistent with its optical surface brightness profile and lack of current star formation (Paper 1).

### Table 1

**GALEX and SDSS Photometry of J1229+02**

| Filter | \( \lambda_p^a \) | \( \Delta \lambda_{100^a} \) | Pipeline mag. | \( A_V \) (mag) | Corrected mag. | \( \log f^d \) | \( \log L^e \) |
|--------|-----------------|-----------------|---------------|-----------------|-----------------|-----------------|-----------------|
| FUV    | 1535            | 255             | 22.229 ± 0.034 | 0.135 ± 0.012   | 22.16 ± 0.06    | −13.79 ± 0.02   | 39.10 ± 0.05    |
| NUV    | 2301            | 730             | 21.110 ± 0.010 | 0.147 ± 0.009   | 20.96 ± 0.03    | −13.21 ± 0.01   | 39.69 ± 0.02    |
| u      | 3557            | 558             | 18.674 ± 0.050 | 0.082 ± 0.001   | 18.59 ± 0.10    | −12.76 ± 0.04   | 40.14 ± 0.07    |
| g      | 4702            | 1158            | 17.284 ± 0.007 | 0.064 ± 0.001   | 17.22 ± 0.03    | −12.13 ± 0.01   | 40.76 ± 0.03    |
| r      | 6176            | 1111            | 16.733 ± 0.007 | 0.044 ± 0.001   | 16.69 ± 0.04    | −12.17 ± 0.02   | 40.72 ± 0.03    |
| i      | 7490            | 1045            | 16.481 ± 0.008 | 0.033 ± 0.001   | 16.45 ± 0.03    | −12.27 ± 0.01   | 40.62 ± 0.03    |
| z      | 8947            | 1125            | 16.286 ± 0.026 | 0.024 ± 0.001   | 16.26 ± 0.06    | −12.32 ± 0.02   | 40.57 ± 0.04    |

Notes.

a Filter pivot wavelength and rectangular width in units of Å, calculated using the filter’s effective area (GALEX; Morrissey et al. 2007) or photometric response (SDSS; Doi et al. 2010) curves.
b Pipeline FUV and NUV magnitudes from GALEX and optical model magnitudes from SDSS.
c Pipeline magnitudes corrected for extinction and photometric calibration uncertainties; see the text for details.
d Logarithm of integrated galaxy flux in the filter bandpass in units of erg s^{-1} cm^{-2}.
e Logarithm of integrated galaxy luminosity in the filter bandpass in units of erg s^{-1}.

3.1. Ultraviolet–Optical Spectral Energy Distribution of J1229+02

The UV–optical SED of J1229+02 was constructed from its GALEX aperture magnitudes and its SDSS model magnitudes. Table 1 lists the wavelength and width of each filter, along with the pipeline magnitudes, total extinction, extinction-corrected magnitude, and integrated flux and luminosity for J1229+02 in each of the GALEX and SDSS bands.

Galactic foreground extinction was determined using the extinction law of Fitzpatrick (1999) assuming \( R_V = 3.1 \) and \( E(B - V) = 0.017 ± 0.010 \) mag (Schäfetz & Finkbeiner 2011). J1229+02 has no optical emission lines (Paper 1; Section 2) and no H I 21 cm emission \((M_{HI} < 5 \times 10^5 M_{\odot})\); van Gorkom et al. 1993), so there is no evidence of gas or dust in this object; thus, we assume that it has no intrinsic extinction. 3C 273 has a large Galactic latitude \((b \approx 75^\circ)\) and a correspondingly low color excess so that the large fractional errors associated with extrapolating extinction in the GALEX bands still yield modest absolute uncertainties.

In the sixth column of Table 1 we list the extinction-corrected magnitude in each filter. The uncertainty in this quantity is the quadrature sum of the error in the extinction correction and the absolute photometric uncertainty interpolated from the results of Morrissey et al. (2007) where it is called “repeatability” for GALEX and Strateva et al. (2001) for SDSS. These larger uncertainties are propagated through to the uncertainty in the integrated flux, but when calculating the integrated luminosity we use the 2\(\sigma\) uncertainty in each filter. We do this as an ad hoc way of accounting for: (1) the fact that the models to which we are comparing the data are not perfect (i.e., they have errors of their own that are hard to quantify); (2) there may be systematic offsets in the zero-point calibration between the GALEX and SDSS data; and (3) we may have systematically underestimated the GALEX magnitudes relative to SDSS by choosing to use aperture magnitudes.

When calculating the luminosity in each band we assume that J1229+02 is located at a distance of 25.6 Mpc, the luminosity distance at \( cz = 1775 \) km s^{-1}; however, the distances to galaxies in this part of the Virgo cluster are known to be double-valued (Tonry & Davis 1981). For example, the distance to the nearby giant elliptical galaxy NGC 4636 has been determined from surface brightness fluctuations.
and globular cluster luminosity function values to be 16.4 Mpc (mean value given in NED\(^3\)); clearly if J1229+02 is at a similar distance it will have a smaller luminosity (by \(\approx 0.4\) dex). However, since this is a systematic effect it does not change any of our modeled quantities except the galaxy’s stellar mass, which needs to be revised downward by the same factor of \(\approx 0.4\) dex.

In the next two subsections we present a detailed description of the SED modeling (first single-burst and then two-population models) that are allowed by the data. A synthesis of this modeling is presented in Section 3.2.

### 3.1.1. Single-burst Models

In order to model the SED of J1229+02 we utilized a grid of template SEDs from Starburst99 (Leitherer et al. 1999). We used the original Padova models at all available metallicities (metal fractions of 0.0004, 0.004, 0.008, 0.02, and 0.05, corresponding to metallicities of \([\text{Fe}/\text{H}] = -1.54, -0.54, -0.24, +0.15,\) and +0.55, respectively; Asplund et al. 2009) and assumed a Salpeter initial mass function (IMF) with masses ranging from 0.1–100 M\(_\odot\) in all cases. The Padova models were chosen because they are the only models available that have metal fractions below 0.001 (i.e., \([\text{Fe}/\text{H}] < 1.1;\) Asplund et al. 2009). For each metallicity we generated templates with ages ranging from 0.1–10 Gyr in 10 Myr time steps. The templates are generated for a simple stellar population with an assumed mass of 10\(^6\) M\(_\odot\) and must be scaled to match the observed luminosity of J1229+02; this scaling gives an estimate of the galaxy’s stellar mass.

To compare the template SEDs with the observed galaxy luminosities in Table 1, we determined synthetic luminosities in each of the filters by convolving the template SED at each grid point with the filter response functions (Morrissey et al. 2007; Doi et al. 2010). Fitting then proceeded in two steps. First, for each age at a given metallicity we scaled the template luminosities assuming a grid of stellar mass values ranging from \(\log (M/\text{M}_\odot) = 6-9\) in steps of 0.01 dex (hereafter any masses appearing in logarithms are assumed to have units of solar masses) and determined \(\chi^2_{\text{opt}}\), a \(\chi^2\) value using only the optical (\(g, r, i, z\)) data. Then we calculated \(\chi^2_{\text{min}}\) for each age and metallicity, the \(\chi^2\) value between the observed and synthetic luminosities calculated using all of the filters with the stellar mass fixed at the value that minimized \(\chi^2_{\text{opt}}\) at that grid point. The bluest data points (FUV, NUV, and \(u\)-band) are crucial for distinguishing models since the largest variations between younger and older stellar populations occur at \(\lambda \leq 4000\) Å.

The parameters of J1229+02 that we are hoping to estimate with this model are the age, metallicity, and mass of its stellar population under the assumption that all of the stars in the galaxy were formed in a single burst. However, given that we pre-select stellar mass values in our fitting procedure the resulting best-fit values of age and metallicity are conditionally dependent on the choice of stellar mass. The likelihood of our model parameters given the data is

\[ \mathcal{L}([\text{Fe}/\text{H}], t \log M_\odot \propto e^{-\chi^2_{\text{opt}}/2}, \] from which we determine a highest posterior density credible interval for the age of the population at a given metallicity. We do this by finding the likelihood threshold above which 95% of the total likelihood lies and determining the range of ages with likelihoods above that threshold. We interpret this result as an indicative range of ages that produce plausible models.

Table 2 lists the results of our single-burst fits. For each metallicity we list: (1) the reduced \(\chi^2\) of the best-fitting model \((\chi^2_{\text{opt}} = \chi^2_{\text{min}}/7); (2) the percentage of the total likelihood found in models of that metallicity; (3) the mode of the age distribution and indicative range of ages as described above; and (4) the range of plausible stellar masses. To determine the range of plausible stellar masses we found the log \(M_\odot\) values chosen (i.e., values that minimize \(\chi^2_{\text{opt}}\) for a given age and metallicity) by grid points that are above the 95% likelihood threshold. The values quoted in Table 2 indicate the median, minimum, and maximum of this range of stellar masses.

There is clearly some degeneracy in the values in Table 2 since higher metallicity models always prefer younger, less massive bursts than lower metallicity models. Nevertheless, since >99% of the total likelihood in Table 2 is found in the two lowest metallicity models, we infer that the single-burst SED fits prefer models with \([\text{Fe}/\text{H}] < -0.2\). Thus ages in the range ~1.3–3.4 Gyr and stellar masses of log \(M_\odot\) ~ 7.3–7.5 are plausible. It is unfortunate that we were unable to run lower-metallicity grid points to ascertain whether the SED likelihood continues to increase as the metallicity decreases; however, the spectroscopic analysis of Paper 1 and Section 2 are another way of trying to model the galaxy as a single-burst population.

The ages inferred from these two techniques are very similar (we found an age range of 2.1\(^{+1.0}_{-0.5}\) Gyr in Section 2) and the Lick-index fits provided a lower bound to the galaxy metallicity ([\text{Fe}/\text{H}] > -1.7), while our SED fits provide a plausible upper bound.

The left-hand panels of Figure 3 show the best-fitting single-burst model for each metallicity. The reduced \(\chi^2\) value and stellar mass and age of the corresponding model grid point are labeled in each panel. These parameter values, at which the joint likelihood is maximized, are in good agreement with the

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\(^3\) The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
maximal marginal (i.e., individual) values listed in Table 2. Finally, we note that while the minimum \( \chi^2 \) value in the entire grid occurs at a metallicity of \([\text{Fe/H}] = -0.5\) a larger fraction of the points in the \([\text{Fe/H}] = -1.5\) grid have relatively small values of \( \chi^2 \); hence, the lowest metallicity has 63\% of the total likelihood as opposed to the 37\% that is associated with the metallicity of the individual grid point that minimizes \( \chi^2 \) (Table 2).

Both H\(\alpha\) and FUV emission can be used to infer a galaxy’s SFR. Our APO/DIS spectrum of J1229+02 (Section 2) yields \( L(\text{H}\alpha) < 2.4 \times 10^{36} \text{ erg s}^{-1} \) to 3\(\sigma\) significance and the GALEX FUV luminosity in Table 1 corresponds to \( \langle l_{\alpha} \rangle = (3.9 \pm 0.2) \times 10^{24} \text{ erg s}^{-1} \text{ Hz}^{-1} \). Using the conversions of Hunter et al. (2010) the H\(\alpha\) SFR is \( <1.7 \times 10^{-5} M_\odot \text{ yr}^{-1} \) and the FUV SFR is \( (5.0 \pm 0.3) \times 10^{-4} M_\odot \text{ yr}^{-1} \). The higher SFR inferred from the FUV flux is expected since H\(\alpha\) measures star formation over the past 10 Myr, whereas FUV measures star formation in the past 10–100 Myr (Hunter et al. 2010). Furthermore, the FUV image measures star formation over the entire galaxy, while the APO/DIS spectrum only measures H\(\alpha\) flux along the slit. However, even the FUV-derived SFR of J1229+02 is not appreciable, which is consistent with the absorption-line and SED analyses summarized above. If we assume that the youngest stars in J1229+02 formed in a burst that lasted \(~100\) Myr (Bruzual & Charlot 1993) and created \( \log M_\text{b} = 7.5 \) solar masses of stars (i.e., as many stars as we could plausibly explain in a single-burst model) the average SFR during the burst was \(~0.32 M_\odot \text{ yr}^{-1} \), or \(~600\) times the galaxy’s current SFR. This estimate of the galaxy’s peak SFR is \(~3\) times less than the value derived in Paper 1 and is more consistent with other dwarf starbursts.

### 3.1.2. Two-population Models

The single-burst models above provide acceptable fits to the galaxy SED, but given the complex star formation histories inferred for Local Group dwarf spheroidal galaxies (e.g., Mateo 1998; Skillman 2005) it is unlikely that all of the stars in J1229+02 were formed in a single burst. However, we are limited in the complexity of star formation models whose SEDs we can model by the small number of photometric data points at our disposal.

To investigate the percentage of older stars that could be present in J1229+02, we have created two-population SEDs combining an old (10 Gyr) stellar population with \([\text{Fe/H}] = -1.5\) and a younger population with arbitrary age and metallicity. Under these assumptions we introduce only one additional free parameter to our model: \( f_m \), the fraction of the galaxy’s total mass that is contained in the younger population. A related quantity necessary to determine the combined luminosity of the two populations is \( f_L \), the fraction of the galaxy’s light that is contained in the younger population:

\[
 f_L^{-1} = 1 + \frac{(M/L)_{\text{young}}}{(M/L)_{\text{old}}} \left( \frac{1 - f_m}{f_m} \right),
\]

where \( (M/L)_{\text{young}} \) is the mass-to-light ratio of the younger population and \( (M/L)_{\text{old}} \) is the mass-to-light ratio of the older population. These values are clearly wavelength dependent so we approximate them with average quantities and take advantage of the fact that the Starburst99 template spectra are all generated for populations with a fixed mass of \( 10^6 M_\odot \). Thus, we simplify Equation (1) using

\[
 \frac{(M/L)_{\text{young}}}{(M/L)_{\text{old}}} \approx \frac{\langle L_{\lambda}\rangle_{\text{old}}}{\langle L_{\lambda}\rangle_{\text{young}}},
\]

where \( \langle L_{\lambda}\rangle_{\text{old}} \) and \( \langle L_{\lambda}\rangle_{\text{young}} \) are the average model luminosities for the older and younger populations, respectively, in the wavelength range 1000–10000 \( \text{Å} \).

Fitting was performed in much the same way as for the single-burst model except that the grid now includes \( f_m \) (ranging from 0.01–0.99 in steps of 0.01) in addition to age, metallicity, and stellar mass. As in the single-burst case we first optimize stellar mass using only the optical data before determining \( \chi^2 \) from all of our data using the optimal stellar mass for a given grid point from the first fitting step. The additional dimension of the two-population model requires us to marginalize the likelihood over all possible values of \( f_m \) to determine a credible interval on age, and vice versa. Plausible values of the stellar mass are determined in the same way as for the single-burst model.
The results of our fits are listed in Table 2. The majority of the total likelihood is associated with the lowest metallicity model, as in the single-burst case; similarly, the grid point with the smallest $\chi^2$ has a metallicity ([Fe/H] = −0.2) that is different from the metallicity with the highest percentage of the total likelihood. There are some differences between results of the two classes of models, however.

The reduced $\chi^2$ values for the two-population models are both lower and more uniform than the corresponding values for the single-burst models, and there is significantly more likelihood in the [Fe/H] = −0.2 grid points for the two-population models than for the single-burst models. The plausible age distributions for the two-population models decrease appreciably as compared to single-burst models of the same metallicity and the stellar masses of the two-population models are systematically higher than those of the single-burst models.

Two-population models with higher metallicity prefer smaller mass fractions for the younger population, smaller ages for this population, and (generally) larger total stellar masses than lower metallicity models. More than 96% of the total likelihood is associated with the three lowest metallicity models, implying that the two-population SED fits prefer metallicities of [Fe/H] < +0.2. The models at these metallicities have plausible parameter values of $\log M_*$ ~ 7.3–7.8, $f_m \geq 0.6$, and age for the younger population of ~0.7–3.1 Gyr (Table 2).

The right-hand panels of Figure 3 show the best-fitting two-population model for each metallicity, with the reduced $\chi^2$, stellar mass, age, and mass fraction of the corresponding grid point labeled in each panel. Unlike the single-burst model, the points that maximize the joint likelihood are not always in good agreement with the modes of the marginal distributions; in particular, the stellar mass that minimizes the reduced $\chi^2$ is remarkably constant and usually at the high end of the plausible range listed in Table 2.

The results presented in Table 2 and Figure 3 for two-population models assume a fixed age and metallicity of the older stellar population in J1229+02 (10 Gyr and [Fe/H] = −1.5, respectively). To test the robustness of the younger population parameters to this assumption, we have also run models with different assumed values for the fixed age and metallicity of the older population. If the older population is assumed to have the same metallicity as in the models presented above but an age of 7.5 Gyr instead of 10 Gyr, we find nearly identical values for $f_m$ and the stellar mass of J1229+02 as those presented in Table 2, and the inferred age of the younger population decreases by ~5%.

If the age of the older population is fixed at 5 Gyr we begin to find more differences: the total stellar mass of the galaxy is ~0.1 dex smaller and the inferred ages are ~20% younger than the values in Table 2, and the mass fraction peaks at <5% for all metallicities. As the age of the older population decreases the fraction of the total likelihood associated with a metallicity of [Fe/H] = −1.5 increases to ~80%, and the fraction at metallicities of [Fe/H] = −0.5 and −0.2 decrease to ~10% and ~5%, respectively. Nevertheless, >98% of the total likelihood is associated with these three metallicities regardless of the assumed age of the older population.

We also examined two-population models where the metallicity of the older population was fixed at [Fe/H] = −0.5 instead of [Fe/H] = −1.5, and had fixed ages of 10, 7.5, and 5 Gyr as above. We did not intend this particular suite of models to be physically consistent but rather to test the robustness of the values in Table 2 and Figure 3 to the assumed metallicity of the older population, so we allowed the younger population to have any metallicity in our grid (i.e., we allowed the metallicity of the younger population to be smaller than that of the older population). We still find that >90% of the total likelihood is associated with younger populations having the three lowest metallicities in our grid, but the fractions at each of these metallicity values are nearly equal (i.e., ~30% of the total likelihood resides in the unphysical model) so no individual metallicity value is clearly preferred. When we compare these models to the models described above where the older population has the same fixed age but a lower metallicity, we find that the higher metallicity models show very little difference in the total galaxy stellar mass but prefer grid points with a higher mass fraction in the young population ($f_m \sim 30–50\%$ when the younger population has [Fe/H] = −1.5, and $f_m \sim 5–20\%$ for all other metallicities) and a larger age of the young population (~10–30% larger at all metallicities). It seems as if we are seeing the same degeneracy manifest itself in the older population properties as we do in the younger population, where assuming a younger, more metal-enriched older population will lead to similar inferences about the properties of the younger population as assuming an older, less metal-enriched older population.

### 3.2. Summary of Spectral Energy Distribution Fitting

In the preceding subsections we presented the methodology and results of two classes of SED fits performed to J1229+02. The single-burst models (Section 3.1.1) assumed that all of the galaxy’s light was produced by a single stellar population whose age, mass, and metallicity we attempted to estimate. The two-population models (Section 3.1.2) assumed an underlying population of fixed age and metallicity and attempted to estimate the age, mass fraction, and metallicity of the younger population and the combined mass of the two populations. We found that the simpler single-burst models preferred metallicities of [Fe/H] < −0.2, ages of ~1.3–3.4 Gyr, and stellar masses of $\log M_* \sim 7.3–7.5$ for J1229+02 (Table 2), consistent with the values found from the absorption-line analyses of Paper 1 and Section 2.

Adding a second population improves the reduced $\chi^2$ of the best-fit models, but interpreting the two-population models is more complicated since any properties of the younger population depend in a degenerate manner on the assumed properties of the older population. Nevertheless, if we choose an older population with an age of 10 Gyr and a metallicity of [Fe/H] = −1.5 we find that the younger population has a mass fraction of <60%, a metallicity of [Fe/H] < +0.2, and an age of 0.7–3.1 Gyr and the two populations combined have a mass of $\log M_* \sim 7.3–7.8$ (Table 2). Thus, the two-population models find younger ages and larger masses than the single-burst models, and not just because they allow solutions with higher metallicity than the single-burst models.

Since the Lick index absorption-line fits and the single-burst and two-population SED models yield results in good agreement with one another we combine them to yield a conservative range of the parameters of interest that satisfy all of the individual constraints. For the parameters of primary interest we find that the full range of acceptable values for the most recent star formation episode in J1229+02 are: 0.7–3.4 Gyr age at a metallicity of $−1.7 < [\text{Fe/H}] < +0.2$. 

---

**Table 2**

| Metallicity | Mass Fraction | Age | Age of Younger Population | Mass of Younger Population |
|-------------|---------------|-----|---------------------------|-----------------------------|
| [Fe/H] = −0.2 | ~0.6 | ~0.7–3.1 Gyr | ~0.7–3.1 Gyr | ~0.7–3.1 Gyr |
| [Fe/H] = −1.5 | ~0.5 | ~0.7–3.1 Gyr | ~0.7–3.1 Gyr | ~0.7–3.1 Gyr |

---

**Figure 3**

The left-hand panels of Figure 3 show the best-fitting two-population model for each metallicity, with the reduced $\chi^2$, total stellar mass, age, and mass fraction of the corresponding grid point labeled in each panel. Unlike the single-burst model, the points that maximize the joint likelihood are not always in good agreement with the modes of the marginal distributions; in particular, the stellar mass that minimizes the reduced $\chi^2$ is remarkably constant and usually at the high end of the plausible range listed in Table 2.
Of secondary importance, we estimate the stellar mass of J1229+02 to be $7.3 < \log M_{*} < 7.8$ and suggest that if more than one stellar population is present in J1229+02 then the most recent one contains $< 60\%$ of the total galaxy mass.

Using the relative likelihood fractions at each metallicity grid point (Table 2), the most likely model for J1229+02 has a stellar mass of $\log M_{*} \sim 7.5$ and $\sim 10\%$ of this mass is contained in the galaxy’s youngest population, which has an age and metallicity of $\sim 2$ Gyr and [Fe/H] $\sim -1$, respectively. We use these parameters in the next section to consider whether the assertion of Paper 1 that J1229+02 could plausibly produce the 1585 km s$^{-1}$ absorber in the 3C 273 sight line still holds in light of our new results.

4. UPDATED ABSORBER FORMATION MODEL

In Paper 1 we modeled the 1585 km s$^{-1}$ absorber in the 3C 273 sight line as part of a thin shell of material that was ejected from J1229+02 approximately 3.5 Gyr ago during a single massive ($\sim 10^{8} M_{\odot}$) starburst episode. We concluded that the supernovae formed in such a starburst are capable of ejecting all of the galaxy’s gas at the time of the starburst (estimated to be $M_{\text{SN I}} \sim 5 \times 10^{8} M_{\odot}$; Bruzual & Charlot 1993; Rosenberg & Schneider 2002) to the location where the absorber is observed today. However, the observations and analysis of Sections 2 and 3 find a considerably larger recession velocity and younger starburst age for J1229+02 than the values assumed in Paper 1. Here we consider whether simple models of the absorber’s origin in a galactic wind emanating from J1229+02 are still feasible.

We emphasize that there are many possible origins of the absorbing gas in the 3C 273 sight line. As discussed in Section 1, NGC 4409 is $\sim 1.5$ virial radii away from 3C 273 and has a smaller line-of-sight galaxy/absorber velocity difference and a considerably larger luminosity than J1229+02. 3C 273 also lies in the southern extension of the Virgo cluster and the absorber may originate in filamentary substructure in the intracluster medium (Yoon et al. 2012), or even be affected by hot intragroup gas in this vicinity (Stocke et al. 2014). We return to the issue of the galaxy’s environment in Section 4.3.

Our aim in presenting the following analysis is not to convince the reader that J1229+02 must have produced the absorber in the 3C 273 sight line but to explore whether it plausibly could have. This is an interesting question in its own right because of the faint luminosity of J1229+02 ($L \sim 0.015 L^{*}$; Stocke et al. 2013) and the large number of galaxies at similarly faint luminosities; the relationship of quasar absorption line systems to dwarf galaxies is still very much an open question (see Paper 1) and it is only at the very lowest redshifts that galaxy redshift surveys are sensitive enough to detect a representative sample of them.

Paper 1 assumed that the 3C 273 sight line intersects the very edge of an expanding spherical shell since only one absorption component was observed (two would be expected if the sight line intersected the “interior” of a shell with unity covering fraction) and the measured line-of-sight velocity difference between the absorber and the galaxy ($\Delta v_{\text{los}} = 50 \pm 50$ km s$^{-1}$) was consistent with the gas expanding entirely in the plane of the sky at the location of 3C 273. This simplifying assumption no longer holds since our revised line-of-sight galaxy/absorber velocity difference ($\Delta v_{\text{los}} = 190 \pm 13$ km s$^{-1}$) is large.

![Figure 4. Escape speed as a function of radius for a cored dark matter profile (solid black line) and an NFW profile (dashed black line) with a halo mass of $M_{h} = 10.36$. The filled gray region shows the variation in escape speed for the cored profile when the halo mass varies by $\pm 0.25$ dex. The errors on the NFW profile are comparable but omitted for clarity. The data point shows the observed line-of-sight galaxy/absorber velocity difference ($\Delta v_{\text{los}}$) and galaxy impact parameter ($\rho$).](image)

Further, we can no longer support the model of a complete spherical shell since only one absorption component is observed in H I Lyman series and metal lines (Sembach et al. 2001; Tripp et al. 2002); thus, for the spherical shell model of this absorber to survive, the shell must be patchy. Below we attempt to constrain the properties of J1229+02 and its patchy shell of ejecta.

4.1. Ballistic Wind Model

In Section 3.2 we presented a synthesis of the absorption-line and SED modeling of J1229+02, determining that $\sim 10\%$ of the stars (by mass) were formed $\sim 2$ Gyr ago and that the total stellar mass of old and young stars in the galaxy is $\log M_{*} \sim 7.5$. Here we use these values to examine a simple ballistic model of an energy-conserving wind emanating from J1229+02.

4.1.1. Energy-conserving Wind

The relations of Moster et al. (2013) suggest that J1229+02 has a halo mass of $M_{h} = 10.36 \pm 0.25$; if we assume that the halo mass is equal to the virial mass, then J1229+02 has a virial radius of $R_{\text{vir}} \approx 75 \pm 15$ kpc (Stocke et al. 2013). We have used two different halo mass distributions to estimate the mass profile of J1229+02: a cored mass distribution from Salucci et al. (2007) and the “cuspy” Navarro–Frenk–White (NFW) profile (Navarro et al. 1996). The escape speed as a function of radius for these profiles is shown in Figure 4. While the NFW profile (dashed black line) has a larger escape speed for very small radii, as expected, the difference between the two models is never more than 10 km s$^{-1}$. The two models are identical at $R \gtrsim 80$ kpc because the distributions are truncated to ensure that $M_{h} = M_{\text{vir}} \equiv M(R_{\text{vir}})$ as in Stocke et al. (2013).

The observed radial velocity difference between the absorber and J1229+02 is also displayed in Figure 4 at the galaxy impact parameter ($\rho = 81$ kpc at the revised recession velocity of J1229+02). These values are both projected quantities, and thus lower limits to the proper three-dimensional values. The observed velocity difference is comparable to the escape speed...
at $R < 1$ kpc, consistent with J1229+02 producing an unbound wind as the result of its most recent starburst.

We utilize conservation of energy to model the wind’s velocity as a function of radius:

$$v^2(R) = v_w^2 - v_{\text{esc}}^2(R_0) + v_{\text{esc}}^2(R),$$

where $v_w \equiv v(R_0)$ is the initial wind velocity. Figure 4 shows that the escape speed is nearly constant at $R \lesssim 1$ kpc so we adopt $v_{\text{esc}}(R_0) = 150 \pm 30$ km s$^{-1}$ and $R_0 = 0.1$ kpc.

For the wind model to be consistent with the absorption-line and SED models of J1229+02 it must satisfy

$$t_{\text{sb}} = \frac{\int_{R_0}^{R_{\text{obs}}} dR}{v(R)},$$

where $t_{\text{sb}} \sim 2$ Gyr is the age of the starburst and $R_{\text{obs}}$ is the total (i.e., deprojected) galaxy/absorber separation at the time of observation.

For any value of $v_w$ there is a unique value of $R_{\text{obs}}$ that satisfies Equation (4), which we solve for numerically. This relationship is shown in Figure 5, where the solid and dashed lines are defined as in Figure 4 and the horizontal dotted line shows the impact parameter, $\rho$. Since $R_{\text{obs}} \geq \rho$ by definition, we constrain $v_w \gtrsim 170$ km s$^{-1}$ for the ejecta to reach its observed location.

4.1.2. Galaxy/absorber Kinematics

We now have enough information to construct a simple model of the galaxy/absorber geometry. We define $\theta$ to be the angle with respect to the line-of-sight that describes the absorber trajectory, where $\theta = 0^\circ$ if the absorber is moving entirely along the line-of-sight and $\theta = 90^\circ$ if the absorber is moving entirely in the plane of the sky. The deprojected galaxy/absorber velocity difference and physical separation between the galaxy and absorber are then given by

$$\Delta v_{\text{obs}} = \Delta v_{\text{los}} \cos \theta$$

respectively.

These Equations can be used to constrain the relationship of $v_w$ and $\theta$ in two different ways. First, we recognize that $\Delta v_{\text{obs}} \equiv v(R_{\text{obs}})$ and use Equations (3) and (5) to find:

$$\cos \theta = \left[ \frac{v_{\text{los}}}{\Delta v_{\text{obs}}} \left( v_w^2 - v_{\text{esc}}^2(R_0) + v_{\text{esc}}^2(\rho) \right) \right]^{1/2}. $$

Here we have approximated $R_{\text{obs}}$ with $\rho$ in the final term under the square root. Since the value of the escape velocity is relatively small at $R > \rho$ (i.e., $v_{\text{esc}}(\rho) = 50 \pm 15$ km s$^{-1}$; Figure 4) this substitution has little effect on the final result and leaves $v_w$ as the only unknown on the right-hand side of Equation (7). This relationship is shown as the solid black line in Figure 6.

Similarly solving for sin $\theta$ as a function of $v_w$ by combining Equations (4) and (6) yields the solid blue line in Figure 6. Unfortunately, we cannot derive an analytic expression for this relationship since we solve Equation (4) numerically for the value of $R_{\text{obs}}$ at which the integral equals a given $t_{\text{sb}}$. The dashed lines in Figure 6 show the propagated uncertainties associated with varying the halo mass by $\pm 0.25$ dex, and the shaded region indicates where the two constraints agree: $\theta = 12.5^\circ$ degrees and $v_w = 240 \pm 25$ km s$^{-1}$. This initial wind velocity is large but still reasonable for a supernova-driven wind (Mac Low & Ferrara 1999; Martin 1999) in either a large or small galaxy; i.e., the supernovae blast wave velocity is independent of galaxy mass and luminosity.

The concordance range of $\theta$ yields $R_{\text{obs}} = 390^{+70}_{-110}$ kpc and $\Delta v_{\text{obs}} = 195 \pm 15$ km s$^{-1}$, which are $\sim 5$ times $R_{\text{vir}}$ and $\sim 9$ times $v_{\text{esc}}(R_{\text{obs}})$, respectively. These results suggest that if J1229+02 formed a galaxy wind as a result of its most recent episode of star formation $\sim 2$ Gyr ago, then any ejecta associated with that wind have escaped the galaxy easily and traveled to very large distances if unimpeded.
4.2. The Gaseous Shell Surrounding J1229+02

Now that the galaxy/absorber kinematics have been examined in the context of an energy-conserving galaxy wind we turn our attention to estimating the amount of material that could have been ejected from dwarf given its initial wind velocity (Section 4.2.1) and the amount of material that can be inferred to surround J1229+02 if the 1585 km s$^{-1}$ absorber in the 3C 273 sight line is part of a shell of ejecta (Section 4.2.2).

4.2.1. Mass Estimate from Wind Energetics

Our synthesis model (Section 3.2) suggests that J1229+02 formed $\sim 3 \times 10^6 M_\odot$ of stars (10% of $\log M_\odot = 7.5$) in a starburst $\sim 2$ Gyr ago. Using a Salpeter IMF from 0.1 to 130 $M_\odot$, this corresponds to $\sim 2 \times 10^8$ stars with $M > 8 M_\odot$ that will create supernovae. Assuming $10^{51}$ erg of kinetic energy per supernova was converted to bulk motion with an efficiency of 3–30% (Koo & McKee 1992a, 1992b; Ciofi & Shull 1991) the starburst provided $\log (E_k/\text{erg}) \approx 53.9$–54.9 of kinetic energy to power a galactic wind. Fewer young stars are created in this model compared to the value assumed in Paper 1 ($\geq 10^8 M_\odot$), so our estimate of the available kinetic energy is $\sim 1.4$ dex less than previously.

Combining the kinetic energy that the starburst injected with the initial wind velocity from our kinematic model suggests that

$$M_{\text{shell}} = \frac{2E_k}{\nu_w}$$  (8)

of gas could have been entrained in a wind and ejected from J1229+02. Using the value of $\nu_w = 240 \pm 25$ km s$^{-1}$ from Section 4.1.2 suggests that $M_{\text{shell}} \sim (7 \pm 4) \times 10^6 M_\odot$, which is more than the total mass of stars created in the burst.

4.2.2. Mass Estimate from Absorber Properties

In this subsection we examine the ionization conditions of the 1585 km s$^{-1}$ absorber near the 3C 273 sight line with the goal of estimating the density of the absorbing material. When combined with the observed column density this density gives an estimate of the absorber’s line-of-sight thickness, which can be used to constrain the thickness of any shell of material that may have been ejected from J1229+02, and subsequently to estimate the amount of mass contained in that shell.

*Far Ultraviolet Spectroscopic Explorer (FUSE)* observations of 3C 273 revealed seven high-order Lyman series lines (Lyβ–Lyθ) that constrain the H I column density and Doppler parameters of the 1585 km s$^{-1}$ absorber to be $\log N_{\text{H I}} = 15.85^{+0.10}_{-0.08}$ and $v_{\text{HI}} = 16 \pm 1$ km s$^{-1}$, respectively (Sembach et al. 2001). Tripp et al. (2002) combined these FUSE observations with a high signal-to-noise echelle spectrum from the Space Telescope Imaging Spectrograph (STIS) aboard *HST* to construct detailed photoionization models of the absorber. These CLOUDY models (Ferland et al. 1998) indicate that the absorber has a metallicity of $[\text{C/H}] = -1.2^{+0.2}_{-0.3}$, a silicon overabundance of $[\text{Si/C}] = +0.2 \pm 0.1$, a density of $\log n_H = -2.8 \pm 0.3$, and a line-of-sight thickness of $D = N_{\text{H I}}/N_{\text{HI}} = 70^{+280}_{-60}$ pc (Tripp et al. 2002).

3C 273 was also observed with the Cosmic Origins Spectrograph (COS) aboard *HST* on 2012 Apr 22 as part of GTO program 12038 (PI: J. Green). The data were reduced and absorption line properties measured as detailed in Keeney et al. (2013) and Stocke et al. (2013). Table 3 shows the ion column densities used in the Tripp et al. (2002) analysis compared to those found in the COS spectrum.

Assuming the H I column density of Sembach et al. (2001), we have generated a photoionization model of the 1585 km s$^{-1}$ absorber using the COS values from Table 3 and the same methodology as in Stocke et al. (2013). The absorber was modeled as a plane-parallel slab illuminated by the extragalactic ionizing background of Haardt & Madau (2012). We assumed that no ionizing flux from hot stars in J1229+02 would reach the absorber location (nor is any expected; see Figure 3). This new model is shown in Figure 7 and finds $\log (Z/Z_\odot) = -0.8^{+0.3}_{-0.2}$, $\log n_H = -2.8 \pm 0.1$, and $D = 130^{+45}_{-30}$ pc. Unlike the Tripp et al. (2002) analysis, we have assumed relative solar abundances and only varied the metallicity, Z, and ionization parameter, $U$. While this photoionization model and the model of Tripp et al. (2002) vary in their details, they infer very similar properties for the absorbing gas. We note, however that the metallicity in our new model is higher than the value found by Tripp et al. (2002).

Despite the many similarities in absorber properties between our models and those of Tripp et al. (2002), there are systematic uncertainties in our results. We have not explored the possibility that the absorber is collisionally ionized, but we...
think that this is unlikely due to its relatively high \( \text{H}^\text{I} \) column density and non-detection in any ion more highly ionized than \( \text{Si} \text{m} \). We have modeled all of the observed ions as arising in the same phase of gas, which we feel is relatively safe given the low ionization of all the detected species (\( \text{H}^\text{I}, \text{C} \text{m}, \text{Si} \text{m}, \text{Si} \text{m} \)) and their velocity alignment in the STIS data (which has a more stable wavelength solution than COS; Tripp et al. 2002). Other limitations of our simple models are that we have not considered non-equilibrium effects, nor have we explored different UV background shapes to see how they affect our results.

Both our model and that of Tripp et al. (2002) infer a density of \( n_\text{H} \sim 1.6 \times 10^{-3} \text{ cm}^{-3} \) and a line-of-sight thickness of \( D \sim 100 \text{ pc} \) for the 1585 km s\(^{-1}\) absorber toward 3C 273. If we assume that ejecta from J1229+02 formed a fully-filled spherical shell of uniform density and thickness \( dR \approx D \cos \theta \) and radius \( R_{\text{obs}} \) then the shell has a mass of

\[
M_{\text{shell}} = m_\text{H} n_\text{H} V_{\text{shell}}
= \frac{4\pi m_\text{H} n_\text{H}}{3} [R_{\text{obs}}^3 - (R_{\text{obs}} - dR)^3].
\]

Using the values of \( R_{\text{obs}} \) and \( \theta \) from Section 4.1 yields \( M_{\text{shell}} \sim 10^{10} M_\odot \), much larger than the supernovae associated with the last burst of star formation in J1229+02 were capable of producing (Section 4.2.1).

The varying estimates of the shell mass from Equations (8) and (9) imply that the shell of ejecta is partially covered, with \( f_c \ll 1\% \) of its surface containing material similar to that which we observe toward the 3C 273 sight line if all of the observed material originated in J1229+02. This fraction is so small that it is unlikely that a ballistic wind from J1229+02 created the 1585 km s\(^{-1}\) absorber.

### 4.3. The Effect of Galaxy Environment

Section 4.1 specifies the simplest possible wind model, where the galaxy is treated in isolation and the ejecta do not interact with any other material after the time of ejection. It therefore presents a limiting case of the farthest that the galaxy could have ejected material in the time since the last episode of star formation.

We know that J1229+02 resides in a rich galaxy environment, however, with ample gaseous medium with which wind ejecta can interact (Yoon et al. 2012; Stocke et al. 2014). Such interactions would slow down the ejecta with respect to the ambient medium. The galaxies in this part of the Virgo cluster have a velocity centroid of \( \sim 1600 \text{ km s}^{-1} \) (Yoon et al. 2012; Stocke et al. 2014), similar to the velocity of the 3C 273 absorber. Given that the velocity of J1229+02 is 1775 km s\(^{-1}\), if we assume that the ambient gaseous medium has a similar velocity to the surrounding galaxies then the interaction of any ejecta with this medium would cause the measured value of \( \Delta v_{\text{los}} \) to be larger than the value associated with the initial wind ejection, \( \Delta v_{\text{los,wind}} \). Similarly, if the ejecta do not travel ballistically for the entire time between ejection and observation then the relevant time to use in Equation (4) is not \( t_{\text{sh}} \) but rather \( t_{\text{ball}} \), the time that the ejecta traveled ballistically.

Combining Equations (8) and (9) and accounting for partial covering yields

\[
v_{\text{w}}^2 = \frac{3E_k}{2m_\text{H} n_\text{H} f_c} \left[ \frac{\rho}{\sin \theta} - \left( \frac{\rho}{\sin \theta} - D \cos \theta \right)^3 \right]^{-1/2}. \tag{10}
\]

This relationship is shown in Figure 8 for several values of \( f_c \). For the shell to escape J1229+02 we require \( v_{\text{w}} \gg v_{\text{los}}(R_0) \) (horizontal dotted line; see Figure 4), which sets limits of \( \theta > 84^\circ (f_c = 1), \theta > 78^\circ (f_c = 0.5), \) and \( \theta > 50^\circ (f_c = 0.1) \). Thus, the absorber trajectory must be close to the plane of the sky for any plausible value of \( f_c \).

The most plausible models are those where \( f_c \gtrsim 0.5 \), for which \( \theta \gtrsim 80^\circ \) and \( R_{\text{obs}} \approx \rho \) (i.e., the values assumed in Paper 1); substituting \( \rho \) for \( R_{\text{obs}} \) in Equation (4) yields \( t_{\text{ball}} \lesssim 1.5 \text{ Gyr} \). Regardless of the value of \( f_c \), Equation (8) indicates that the shell mass can be no more than \( 2E_k/\rho_{\text{esc}}(R_0) \sim (3.5 \pm 1.2) \times 10^7 M_\odot \), which is about 10 times more than the mass of stars formed in the most recent burst in J1229+02.

### 4.4. Summary of Wind Models

In this Section we have explored whether J1229+02 is capable of producing the absorption seen at 1585 km s\(^{-1}\) in the 3C 273 sight line. In Section 4.1 we developed an energy-conserving wind model and attempted to model the galaxy/absorber kinematics in the context of this model. We assumed that J1229+02 last formed stars \( t_{\text{sh}} \sim 2 \text{ Gyr} \) ago and the resultant supernovae explosions created a wind that is responsible for the observed line-of-sight galaxy/absorber velocity difference of \( \Delta v_{\text{los}} = 190 \pm 13 \text{ km s}^{-1} \). We further assumed that this wind has traveled ballistically for the entire time \( t_{\text{sh}} \) since formation and that it is responsible for the current lack of gas in J1229+02 (van Gorkom et al. 1993); i.e., we assumed that J1229+02 is solely responsible for the formation of the absorber.

Under these assumptions the wind emanating from J1229+02 must intersect the 3C 273 sight line at an angle of \( \theta \approx 10^\circ \) with respect to the line of sight and had an initial velocity of \( v_{\text{w}} \approx 240 \text{ km s}^{-1} \). Deprojecting the observed galaxy/absorber separation on the sky (\( \rho = 81 \text{ kpc} \)) and velocity difference (\( \Delta v_{\text{los}} \)) using Equations (5) and (6) yields \( R_{\text{obs}} \approx 5\rho \) and
\( \Delta v_{\text{obs}} \approx \Delta v_{\text{los}} \). Thus, this ballistic model is the limiting case of the farthest that J1229+02 could have expelled material in a time \( t_b \); as such, it is a “maximal expansion” model where the three-dimensional velocity is projected almost entirely onto the line of sight.

In Section 4.2 we considered the implications of this ballistic wind model for the gaseous shell of material surrounding J1229 +02, of which the absorber is a part under our assumptions. We find that the supernovae explosions associated with the last burst of star formation in J1229+02 would provide enough kinetic energy to expel a shell of gas with a mass comparable to the mass of stars formed in the burst. However, a thin spherical shell with uniform density comparable to that which we derive from the 3C 273 absorber (\( n_H \sim 1.6 \times 10^{-3} \text{ cm}^{-3} \)) and radius \( \sim 5 \rho \) would have a much larger mass that is comparable to the galaxy’s entire halo mass. Thus, we reject the simple ballistic wind model for the formation of the absorber due to its untenably low covering fraction.

In Section 4.3 we surmised that one consequence of the rich galaxy environment near J1229+02 is that the observed \( \Delta v_{\text{obs}} \) may not be indicative of the initial wind velocity due to interactions of the wind ejecta with the ambient gaseous medium. We develop a relation between the initial wind velocity and trajectory for a shell of a given covering fraction, \( f_c \) (Equation 10), and find that for \( f_c \gtrsim 0.5 \) the wind velocity is larger than the galaxy’s escape velocity only for \( \theta \gtrsim 80^\circ \), which implies \( R_{\text{abs}} \approx \rho \). This high-covering-fraction model thus represents a “minimal expansion” model in which the galaxy/absorber separation is projected almost entirely onto the plane of the sky.

The only robust conclusion that we can draw from this analysis is that J1229+02 cannot be solely responsible for the formation of the 1585 km s\(^{-1}\) absorber in the 3C 273 sight line. The ballistic wind model explicitly tried to account for the absorber by an escaping wind from J1229+02 alone and failed because the supernovae associated with the galaxy’s most recent star formation episode had insufficient kinetic energy to fill a large fraction of the surface of an expanding shell with material similar to that which we observe toward 3C 273. The three-dimensional galaxy/absorber separation is projected to lie almost entirely on the plane of the sky or along the line of sight, respectively, and find that any wind ejecta from J1229+02 must interact with gas outside of the galaxy to explain the presence of the 3C 273 absorber in both cases. Therefore, we conclude that J1229+02 cannot be solely responsible for the formation of the absorber.

The properties of J1229+02 that led us to speculate in Paper 1 that it could plausibly form a starburst wind are its post-starburst optical spectrum and its present-day lack of gas (van Gorkom et al. 1993). While these properties remain unchanged, we no longer find compelling evidence that the 1585 km s\(^{-1}\) absorber in the 3C 273 sight line was formed solely by a wind escaping from J1229+02. We have revised the recession velocity of J1229+02 upward from the value presented in Paper 1, however, and argue in Section 4.3 that the galaxies in the southern extension of the Virgo cluster have a centroid of \( \sim 1600 \text{ km s}^{-1} \), comparable to the absorber velocity (Yoon et al. 2012; Stocke et al. 2014). If we assume that any intracluster gas in the vicinity has a similar velocity then J1229+02 is moving through this medium with a relative velocity of \( \sim 175 \text{ km s}^{-1} \). This velocity is high enough that we may not require supernovae associated with the last burst of star formation in J1229+02 to explain its present-day lack of gas (i.e., ram pressure stripping may be a viable alternative).

Another consequence of the potentially high peculiar velocity of J1229+02 is that it may have moved an appreciable distance on the sky since its last burst of star formation \( \sim 2 \text{ Gyr} \). If J1229+02 has a velocity of \( \sim 100 \text{ km s}^{-1} \) in the plane of the sky then it has traveled \( \sim 200 \text{ kpc} \) on the sky (\( \sim 28^\circ \), and the age of its most recent star formation episode were determined from the SDSS spectrum and found to be consistent with the values obtained for the single-burst SED models of Section 3 and the Lick index analysis of Paper 1. Thus, the conclusion that this dwarf will not continue to form new stars but rather fade to a very low luminosity (\( M_B \gtrsim -14 \)) is confirmed.

In Section 3 we examined the impact of both single-burst and two-population models for the star formation history of J1229+02 on the galaxy’s UV–optical SED. The GALEX UV magnitudes were essential for distinguishing between models of different ages. We find that both single-burst and two-population star formation histories provide acceptable fits to the galaxy’s SED, but the best-fit two-population models have significantly smaller reduced \( \chi^2 \) values than the best-fit single-burst models (see Figure 3). The absorption-line fits and SED analysis yield comparable estimates for the age and metallicity of the youngest stellar population in J1229+02. We combine these results to find a full range of acceptable values for the age, metallicity, and mass fraction of this population of 0.7–3.4 Gyr, \( 1.7 < [\text{Fe/H}] < +0.2 \), and \( f_m < 0.6 \), respectively, and estimate the total stellar mass of J1229+02 to be \( 7.3 < \log M_{\ast} < 7.8 \).

In Section 4 we attempted to synthesize these results into a simple model of the galaxy/absorber system to confirm whether the conclusion of Paper 1 that a wind emanating from J1229+02 could plausibly form the 3C 273 absorber is still valid given our new data. Given the broad range of acceptable star formation histories for J1229+02, we choose fiducial values of \( f_m \sim 0.1 \), \( \log M_{\ast} \sim 7.5 \), \( t_b \sim 2 \text{ Gyr} \), and \( [\text{Fe/H}] \sim -1 \) for this analysis. We explore both minimal and maximal expansion models where the three-dimensional galaxy/absorber separation is projected to lie almost entirely on the plane of the sky or along the line of sight, respectively, and find that any wind ejecta from J1229+02 must interact with gas outside of the galaxy to explain the presence of the 3C 273 absorber in both cases. Therefore, we conclude that J1229+02 cannot be solely responsible for the formation of the absorber.
corresponding to a proper motion of $\sim 10^{-3}$ mas yr$^{-1}$) in the past 2 Gyr. Thus, the current proximity of J1229+02 to the 3C 273 sight line may be coincidental as it could be caught in the act of passing by. This is a fundamental ambiguity in trying to associate QSO absorption line systems with individual galaxies since there can be a large physical distance between the galaxy and the QSO sight line and the galaxy has a proper motion that is too small to be measured; thus, there is no way to know the relative positions of the galaxy and the QSO sight line several Gyr in the past when the absorbing material was presumably expelled from the galaxy.

It is instructive to look at the galaxy/absorber pair studied here in the larger context of what is being learned about the circumgalactic medium (CGM) of galaxies from COS observations. Targeted and serendipitous galaxies located within $\sim 0.5 R_{\text{vir}}$ of the QSO sight line typically show low- or intermediate-ionization absorption from H\textsc{i} and metal-lines that are well-fit by photoionization models similar to those presented in Section 4.2.2 (Prochaska et al. 2011; Tumlinson et al. 2011; Werk et al. 2013, 2014; Stocke et al. 2013). These close-in CGM systems often have strong collisionally-ionized O\textsc{vi} absorption as well (Tumlinson et al. 2011; Stocke et al. 2013, 2014).

The situation is less clear for galaxies located $\gtrsim 1 R_{\text{vir}}$ from the QSO sight line (i.e., those with similar separations to J1229+02 and 3C 273), however. At these distances the incidence of Ly$\alpha$ absorption is similar to that for the closer galaxies, but the incidence of metals is not. Metals are not detected for $\sim 50\%$ of galaxies with $\rho \sim 1 R_{\text{vir}}$, and when they are detected it is typically only in higher-ionization species such as O\textsc{vi} and C\textsc{iv} (e.g., see Table 3 and Figures 8 and 11 of Stocke et al. 2013). Therefore, the connection between individual galaxies located $\sim 1 R_{\text{vir}}$ from a QSO sight line and the detected QSO absorption-line system is ambiguous. While the relatively low ionization of the 1585 km s$^{-1}$ absorber in the 3C 273 sight line and the unusual properties of J1229+02 compared to other pairs at these separations made it seem more likely that a definitive association between the two could be made, we have not been able to make a strong case for a causal relationship.

The Q1230 + 0115 sight line is located near 3C 273 on the sky (\approx 1° separation) and has an absorption-line system at comparable velocity (1700 km s$^{-1}$; Rosenberg et al. 2003) and H\textsc{i} column density ($\log N_{\text{HI}} = 15.27 \pm 0.22$; Tilton et al. 2012) to the 3C 273 absorber studied here (1585 km s$^{-1}$ and $\log N_{\text{HI}} = 15.85^{+0.10}_{-0.08}$, respectively; Sembach et al. 2001). The Q1230 + 0115 absorber is also detected in several metal species, including C\textsc{ii}, C\textsc{iv}, Si\textsc{ii}, and Si\textsc{iv} (Rosenberg et al. 2003). The region around Q1230 + 0115 has been surveyed for galaxies to comparable depth to the region around 3C 273. The galaxy that is the fewest number of virial radii from the 1700 km s$^{-1}$ absorber is NGC 4536, which has $\rho = 550$ kpc $\approx 2.1 R_{\text{vir}}$ and $\Delta V_{\text{los}} \approx 100$ km s$^{-1}$. There are several smaller galaxies within 400 km s$^{-1}$ of the absorber redshift that are located closer to the sight line, but they all have $\rho > 240$ kpc. Thus, it is unlikely that a single galaxy is responsible for producing the metals observed in this absorber either.

We have been unable to find galaxies located closer than $\sim 1 R_{\text{vir}}$ to very low redshift metal-line absorbers in the 3C 273 and Q1230 + 0115 sight lines despite surveying to very faint levels ($L < 0.001 L^*$; Stocke et al. 2013) in both cases. In this Paper we concluded that the dwarf post-starburst galaxy J1229+02 could not create the 3C 273 absorber on its own and the closest galaxy to the Q1230 + 0115 absorber (in terms of virial radii) is twice as far from the sight line as J1229+02. Thus, these absorbers appear to have truly intergalactic (i.e., composite), rather than circumgalactic (i.e., single-galaxy), origins. These results suggest that the only truly circumgalactic absorbers may be those located within $\sim 0.5 R_{\text{vir}}$ of galaxies (e.g., Stocke et al. 2013).
