AEGIS: THE NATURE OF THE HOST GALAXIES OF LOW-IONIZATION OUTFLOWS AT Z < 0.6
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ABSTRACT

We report on a signal-to-noise–limited search for low-ionization gas outflows in the spectra of the 0.11 < z < 0.54 objects in the Extended Groth Strip (EGS) portion of the Deep Extragalactic Evolutionary Probe 2 (DEEP2) survey. Doppler shifts from the host galaxy redshifts are systematically searched for in the Na I λ 5890, 96 doublet (Na I D). Although the spectral resolution and signal-to-noise limit us to study the interstellar gas kinematics from fitting a single doublet component to each observed Na I D profile, the typical outflow often seen in local luminous-infrared galaxies (LIRGs) should be detected at ≳ 6σ in absorption equivalent width down to the survey limiting signal-to-noise (∼ 5 pixel−1) in the continuum around Na I D. The detection rate of LIRG-like outflow clearly shows an increasing trend with star-forming activity and infrared luminosity. However, by virtue of not selecting our sample on star formation, we also find a majority of outflows in galaxies on the red sequence in the rest-frame (U − B, M_B) color-magnitude diagram. Most of these red-sequence outflows are of early-type morphology and show the sign of recent star formation in their UV-optical colors; some show enhanced Balmer Hβ absorption lines indicative of poststarburst as well as high dust extinction. These findings suggest that galactic-scale outflow may play an important role in quenching star formation in the host galaxies on their way to the red sequence. Furthermore, outflows well outlive starbursts and present significant columns, so the fate of relic winds may be studied well in galaxies at their poststarburst phase to constrain the gaseous feedback models.

Subject headings: galaxies: active — galaxies: evolution — galaxies: formation — galaxies: stellar content — ISM: jets and outflows

1. INTRODUCTION

A number of large-scale galaxy surveys of unprecedented volume and depth are steadily mapping out the luminous constituents of the universe out to higher redshifts. The ΛCDM cosmological paradigm describes the gravity-driven assembly history of the universe quite successfully on the largest physical scales. Yet our understanding of the universe remains largely incomplete on the galaxy scales where the astrophysical processes involving stellar evolution and feedback of interstellar and intergalactic matter are essential; baryons can cycle through these in an intricate, multiphase manner. Gaseous feedback processes have been gaining serious attention, since theoretical predictions of the growth of luminous structure are highly sensitive to the “prescriptions” for these small-scale, subgrid physics (e.g., Croton et al. 2006; Bower et al. 2006; Hopkins et al. 2006), yet the observational constraints are still relatively scarce.

Absorption-line probes of gas entrained in galactic “superwinds” (e.g., Chevalier & Clegg 1985; Heckman et al. 1990) have been effective in constraining how much matter could be carried by outflows through the lines in the rest-frame optical (e.g., Heckman et al. 2000; Rupke et al. 2002, 2005b; Martin 2005) and ultraviolet (e.g., Heckman et al. 2001; Schwartz et al. 2006), which may pollute intergalactic media and eventually deplete host galaxies of fuel for further star forma-

cation. The low-ionization absorption line studies suggest that a considerable amount of neutral gas may be carried away by outflows, ∼ 10^1−10^7 M☉ in dwarfs (Schwartz & Martin 2004) and ∼ 10^8−10^10 M☉ in ultraluminous infrared galaxies (ULIRGs; Martin 2005; Rupke et al. 2005b). The column density of outflowing cool matter, however, can only be estimated after making a series of crude assumptions on its geometry, ionization state, dust-depletion factor, and metallicity. Although the reliability of these mass outflow estimates could therefore be questioned, an unambiguous detection of outflow is relatively straightforward in finding a Doppler-shifted absorption component in a line complex of interest. Nonetheless, a vast majority of existing studies of outflows have focused on galaxies selected a priori to have high star formation rates (SFRs), from dwarf starburst galaxies (e.g., Schwartz & Martin 2004) and luminous infrared galaxies (e.g., Martin 2005, 2006; Rupke et al. 2005a,b) in the local universe to Lyman-break galaxies at high redshifts (e.g., Shapley et al. 2003); see Veilleux et al. (2005) for a recent review. Although winds have been unambiguously detected in these systems, much work remains to be done in characterizing outflows in terms of their host galaxy properties in a large, relatively unbiased sample.

The Na I λ 5890, 96 doublet (Na I D) absorption can be stellar or interstellar in origin yet is a useful line for the census of cool winds in the interstellar medium (ISM). Since it is an absorption line measured against the background light of host galaxies, its blue/redshift relative to the systemic redshift can be measured relatively well. The Na I D absorption line directly traces cool (T ∼ 100 K) gas which may directly fuel star formation. In (U)LIRGs, ∼ 10% of the dynamical mass can be entrained in cool outflows (Rupke et al. 2005b; Martin 2006), suggesting that the bulk of outflowing mass resides at the cool phase. The Na I D doublet is a resonance line and forms among the most prominent absorption lines detectable...
out to $z \sim 0.5$ in optical spectra.

There is a pressing need to extend the study of outflows to the systems with a lower SFR as well as at a later stage of star formation. For one thing, the observed spatial extent of outflows and a simple dynamical argument suggest that outflowing gas clouds may outlive starbursts or active galactic nuclei (AGNs) which may drive outflows (Martin 2006). Recently, Tremonti et al. (2007) found that $z \sim 0.5$ massive poststarburst galaxies, observed at 1–2 Gyr after an intense episode of star formation, host outflows almost as strong or even greater as those observed in LIRGs. Since outflows may carry away from galaxies a significant fraction of gas mass that would otherwise be available for further star formation, knowing the “fate” of outflowing matter is clearly of interest.

In this paper, we present the result from a systematic search for Na I D outflows in a flux-limited sample of galaxies, drawn from the Extended Groth Strip (EGS) portion of the Deep Extragalactic Evolutionary Probe 2 survey (DEEP2; Davis et al. 2003). Since the EGS field has been extensively observed by a wide array of multi-wavelength missions as part of the All-wavelength Extended Groth Strip Survey (AEGIS; Davis et al. 2003), we are able to characterize our spectroscopically-selected sample in view of various physical quantities. Although Na I D is a resonance line and among the most prominent of absorption lines in the visible, rigorous absorption analysis needs high signal-to-noise (S/N) continuum, which is a requirement not quite satisfied by the vast majority of 1-hr integration spectra from the DEEP2 survey. Co-adding a number of low-S/N spectra from a set of subsamples to improve the effective S/N is a sensible approach. Yet even such stacking analyses are limited a priori by numerous ways in which subsamples can be constructed; some prior knowledge must be gained about the subsampling schemes in which the desired information can best be elucidated. In order to initiate the effort of unbiased census of outflows in modern spectroscopic galaxy surveys as well as to motivate ensuing stacking analysis with proper subsampling schemes, it is still beneficial to take an approach to seek evidence of outflows in individual spectra.

Although the ambitious goal would be to estimate the quantities that are useful for improving the prescriptions for cosmological semi-analytical simulations, such as outflow detection rate and mass-loading factor in a robust volume-limited sample, in this paper our focus is on characterizing the property of galaxies that host LIRG-like outflows, using a rich set of multiwavelength observations from the AEGIS survey. We first describe the data, selection, and analysis method for the Na I D sample in § 2. The host galaxies of outflows, as defined from the Na I D kinematics, are then studied in view of their UV, optical, and infrared properties in § 3. We then note a few caveats, frame our findings in the larger context of galaxy evolution (§ 4), and summarize the paper (§ 5). Throughout this paper, we adopt the standard ΛCDM cosmology, $(\Omega_m, \Omega_\Lambda) = (0.3, 0.7)$, with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. DATA AND ANALYSIS

2.1. DEEP2 Spectra

The EGS, covering $\approx 0.5$ deg$^2$, is one of four fields observed in the DEEP2 survey (see Coil et al. 2004; Davis et al. 2003, 2004, for the descriptions of the survey), in which the spectroscopic targets are pre-selected by the Canada-France-Hawaii Telescope (CFHT) BRI photometry (Cuillandre et al. 2001). While the targets in the other three fields are pre-selected to the apparent magnitude limit of $R_{AB} \leq 24.1$ and by color cuts to the galaxies likely to be at $z \gtrsim 0.7$, such a color cut was used in the EGS to slightly down-weight galaxies at $z \lesssim 0.7$, resulting by design in roughly equal numbers of galaxies above and below $z = 0.7$. The spectra for $\approx 13570$ EGS objects are obtained with the DEIMOS spectrograph on the Keck II telescope (Faber et al. 2003). The 1200 lines mm$^{-1}$ grating centered at $7800 \AA$ and the OG550 order-blocking filter with $1''$ slitwidths are used, which leads to the spectral coverage roughly of $6500 \AA$–$9100 \AA$. The resolution results in $\text{FWHM} \approx 68$ km s$^{-1}$. The data are processed by an automated pipeline to produce (unfluxed) 1D spectra (Newman et al., in preparation). The DEEP2 DEIMOS pipeline produces an inverse-variance vector for each spectrum. In this paper, we use the spectra extracted via a variant of the optimal extraction algorithm presented in Horne (1986).

2.2. Systemic Redshifts

An outflow velocity is measured relative to a systemic redshift of a host galaxy. A major contribution to the uncertainty of outflow velocity therefore comes from the uncertainty in the systemic redshift measurement. Each DEEP2 spectrum is assigned a spectroscopic redshift from $\chi^2$ minimization with a few template spectra and has the accuracy well quantified from repeat observations (30 km s$^{-1}$ in RMS; Willmer et al. 2006). Each redshift measurement has been visually inspected and assigned a redshift quality flag. Nevertheless, we carry out independent redshift measurements using IRAF software package XCSAO (Kurtz & Mink 1998). The primary motivation for an independent set of redshift measurements is to mask the Na I D complex. The Na I D absorption line is among the most prominent features in the visible part of the galaxy spectrum. In the case where a systemic redshift should only reflect the centroid of the stellar motions, Na I D should be excluded from cross correlation with stellar spectral templates, in order to avoid the interstellar components, which may be redshifted or blueshifted from the systemic redshift of the galaxy, to affect the measurement.

We adapt the cross-correlation templates (ID: 24–30) from the fifth data release of the Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2006). The template which yields the smallest uncertainty is generally picked and designated as the systemic redshift of the galaxy. An uncertainty in each redshift measurement is derived from the $r$ statistics, which roughly corresponds to the S/N of cross-correlation peak from which the best redshift estimate is computed (Tonry & Davis 1979). The agreement between XCSAO and DEEP2 redshifts is generally good; for most purposes, the systematic redshift disparity of $cz(XCSAO) - cz(DEEP2) \approx 10$ km s$^{-1}$ is much less than the instrumental resolution and is insignificant. Where precise systemic redshifts are critical, we use XCSAO measurements, since the uncertainty is empirically calibrated and well understood among our sample. The redshift measurement stored in each DEEP2 spectrum almost certainly underestimates the uncertainty in case of gross template mismatch, since only three components are used to generate a template for cross correlation, and $\chi^2$ statistics was computed after continua are removed from them. Each redshift measurement for which $|cz(XCSAO) - cz(DEEP2)| > 2\sigma_{cz}(XCSAO)$ is visually inspected, and the spectrum is either reassigned a red-
shift from another template or removed from the sample.9

2.2.1. Spectral Line Indices

Using the rest-frame band definitions in Table 1, we measure the spectral indices (denoted $W_0$, with the subscript “0” meaning rest frame) of some lines as estimates of their equivalent widths. Each spectral line index is computed via the “flux-summing” method. First, a straight line “pseudocontinuum” is fitted to the variance-weighted pixel flux values from the blue and red straddling continua as defined in Table 1, via the standard Levenberg-Marquardt algorithm. The covariance matrix is used to estimate the uncertainty in the pseudocontinuum. Then at each pixel $i$ with the pixel width $\Delta \lambda_i$ falling within the spectral bandpass defined as “line” in Table 1, the observed flux $f_o$ and the pseudocontinuum flux $f_c$ is used to compute the flux excess or depletion, such that

$$W = -\sum_i \left( \frac{f_o - f_c}{f_c} \right) \Delta \lambda_i$$

yields the equivalent width index in the observed frame. The rest-frame value is computed simply from $W_0 = W/(1+z)$ where $z$ is the redshift of the galaxy. The uncertainty in the index is estimated by formal propagation of uncertainties in $f_c$ and $f_o$ using the above relation. By construction, $W_0 > 0$ Å ($< 0$ Å) corresponds to a line flux seen in absorption (emission), although the physical interpretation is slightly complicated by the fact that both emission and absorption may exist for a line feature, sometimes called emission filling. Although not perfect, a line index gives a good estimate of true equivalent width, when such a problem as emission filling is not significant.

Previous studies have used the equivalent width of the Mg I b λ5167, 73, 85 triplet to estimate the stellar contribution to the Na I D absorption line (Heckman et al. 2000; Rupke et al. 2002; Schwartz & Martin 2004; Rupke et al. 2005a; Martin 2005). The correlation between Na I D and Mg I b equivalent widths in stellar spectra is expected based on the similar mechanisms from which Na and Mg are produced in stars and their roughly similar ionization potentials (5.14 eV and 7.65 eV for Na and Mg, respectively). Heckman et al. (2000), Martin (2005), and Rupke et al. (2005a) all showed high equivalent width ratios of Na I D to Mg I b to be a good indicator of the presence of winds from their samples of infrared-luminous galaxies. This assumption is reasonable provided that a presence of a large column density from the interstellar Na I is required for a secure detection of outflow. In Fig. 1, however, we see evidence that a population of galaxies with outflows would be missed by a high $W_0$(Na I D)/$W_0$(Mg I b) selection scheme. The figure is meant to facilitate a comparison to the existing studies, in which the samples are selected by a high level of star formation (i.e., a high infrared luminosity). As will be discussed later, outflows appear to outline starbursts, and the relic winds may present significant columns to be detected in “poststarburst” galaxies.

2.3. Sample Selection

We systematically search DEEP2 spectra in the EGS field for the coverage of Na I D absorption line and continuum around it (Table 1). An object is removed from our sample if the redshifted Na I D spectral range is at least partially outside the edge or falls on the gap between the blue and red CCD chips. This process reduces the sample to 2248 objects. The spectral baseline of DEEP2 observations restricts our sample to $0.11 < z < 0.54$. For each DEEP2 spectrum, the continuum S/N per pixel ([S/N]$_{pix}$) in the continuum region around Na I D is defined to be the median ([S/N]$_{pix}$) computed from the pixel flux values and their inverse variances registered within the blue and red continua (Table 1). The main selection cut is made at ([S/N]$_{pix}$) $> 5$ around Na I D, reducing the sample to 493 objects. We also remove objects whose Na I D feature is severely compromised by sky emission or atmospheric absorption lines after visual inspection, reducing the sample to 431 objects. The latter cut tends to remove objects at specific redshifts where the redshifted Na I D overlaps with telluric features.

The particular choice of continuum S/N cut is a compromise between the inclusion of more objects for better statistics and the reliability of Na I D velocity measurements. Given the limited spectroscopic S/N, our desire to probe fainter objects is motivated by the well-known, downsizing nature of star formation (e.g., Cowie et al. 1996) and the apparent correlation between the presence of galactic-scale wind and the strength of star formation (e.g., Martin 2005; Rupke et al. 2005b). At low $z$, star formation is expected in optically fainter, low surface brightness galaxies. At high $z$, increasingly brighter galaxies are host to star formation yet become faint in their apparent brightness in the visible. We also expect that the high-S/N spectra are obtained from passive, early-type galaxies, which also tend to be of high surface brightness. All these effects conspire to make the galaxy population of interest to be somewhat elusive in the optical selection used here. Furthermore, the strength of Na I D absorption, both stellar and interstellar, varies widely from galaxy to galaxy, and our ability to detect an outflow depends on the strength of continuum as well as the absorption feature. It is therefore important to get some idea as to what kind of Na I D outflow to which our measurements are sensitive in this study.

In Fig. 2, the distribution of spectral index measurements as a function of continuum ([S/N]$_{pix}$) around Na I D is shown and demonstrates that we cannot obtain reliable Na I D velocity measurements in most spectra (i.e., constitutes the low-S/N sample; see § 2.4 for detail) at ([S/N]$_{pix}$) $\lesssim 6.5$. The detection limit as a function of ([S/N]$_{pix}$) for a fiducial LIRG wind indicate that we are reaching the $\sim 5\sigma$ detection limit for a typical LIRG-type wind in our sample at that continuum S/N level. The distribution of low-S/N measurements suggests that the efficiency of Na I D absorption detection becomes clearly low, as most S/NS in the Na I D velocity measurements lie below the fiducial LIRG wind loci at low continuum ([S/N]$_{pix}$). Thus the selection cut at ([S/N]$_{pix}$) = 5 seems justified, in terms of

9 Throughout this paper, we only use spectra which are tagged DEEP2 ZQUALITY flag of four. Only one object dropped out of the sample because of the failure in the cross-correlation redshift measurement.

10 Over the redshift range, the physical scale corresponding to 1″-slit varies from 2 kpc to 9.5 kpc.
detecting LIRG-like winds at high ($\geq 5\sigma$) confidence. Fig. 2 shows that the success rate of Na i D velocity measurement is a strong function of continuum (S/N)$_{\text{in}}$. Overall, there are 205 objects with successful Na i D velocity measurements, and 226 objects without. We will describe what constitutes a “successful” velocity measurement in the next section.

2.4. Modeling Na i D Absorption Lines

In principle, countless possible configurations of the geometry of individual absorbers along a sightline give rise to an unlimited variety of observed Na i D absorption line profiles; from numerical simulations, several absorbers entrained in a starburst wind are expected to lie along a single sight line (Fujita et al. 2008). In practice, however, the spectral resolution and moderate S/N limits our ability to study more than one component of Na i D doublet in the DEEP2 spectra; multiple absorption components would be seen blended even at sufficient S/N. Due to these limitations, the absorption equivalent width and the physical quantities derived from a Na i D line profile in general may not be uniquely related. Nonetheless, the modeling of the absorption line should be physically motivated, and in this respect we closely follow the method presented by Rupke et al. (2002, 2005a); readers are highly encouraged to find the detail of their absorption line analysis method in those papers. An absorption line is modeled with the wavelength ($\lambda_0$) and the optical depth ($\tau_0$) at the line center, Doppler width ($b_D$), and the covering fraction ($C_f$) in a self-consistent manner. Our confidence intervals on Na i D velocity measurements, however, are obtained via directly carrying out the Markov chain Monte Carlo (MCMC) analysis on the observed spectra with the Rupke et al.-type line-profile modeling, rather than what Rupke et al. (2005a) outlines. In the Appendix, we give a summary of the technique and the analysis method.

MCMC sampling generates a probability density for each model parameter which allows us to visually inspect the quality of our measurements. Except for a couple dozen high S/N spectra, the optical depths cannot be constrained at all; i.e., the probability density for the central optical depth $\tau_0$ usually ends up being distributed roughly uniformly over the allowed range ($0 < \tau_0 < 999$) with a slight enhancement toward lower optical depths. In turn, the highly saturated profile tends to let the covering fraction $C_f$ be distributed near the level of minimum intensity of a Na i D profile. This degeneracy between $\tau_0$ and $C_f$ at low S/N regime is a well-understood property of the model profile employed by Rupke et al. and in this paper; extracting an optical depth in general requires the lineshape to be very well sampled. The distributions of Na i D central wavelengths $\lambda_0$ and Doppler widths $b_D$, on the other hand, are relatively well-behaving even at lower S/N, where their prob-
ability densities roughly become Gaussian.

One especially important caveat of our Na\textsc{i} D velocity measurement is in order. Our interest is in studying the interstellar gas kinematics, so ideally stellar contributions to Na\textsc{i} D should be removed via such a method as fitting template spectra generated from population synthesis models (e.g., Tremonti et al. 2004). The DEEP2 spectra are not rigorously fluxed, however, and we are unable to carry out a similar procedure. This is a substantial limitation in the analysis of galaxy spectra of intermediate- and old-age stellar populations, since their stellar absorption at Na\textsc{i} D becomes strong [Fig. 1; the stellar loci are from Delgado et al. (2005)]. The implication on our definition of outflow velocity will be discussed in § 2.5.

We also do not take any special care of the nebular emission line He\textsc{i} λ 5876, found ∼ 15 Å blueward of Na\textsc{i} D in some spectra. The He\textsc{i} emission line can contaminate the high velocity tail of strong Na\textsc{i} D outflows in (U)LIRGs (e.g., Rupke et al. 2005a; Martin 2005). Upon visual inspection, however, few galaxies in our sample with a good Na\textsc{i} D velocity measurement are found to have their Na\textsc{i} D contaminated by the presence of the He\textsc{i} emission line.

2.4.1. Na\textsc{i} D Velocity and Blueshift Probability

![Graph showing continuum (S/N)\textsubscript{pix} around Na\textsc{i} D](image)

**Fig. 2.**—The S/N (top) and spectral line index (bottom) as a function of continuum (S/N)\textsubscript{pix} around Na\textsc{i} D. The points are denoted by Na\textsc{i} D kinematics: outflow (blue filled circle), systemic (gray cross), inflow (red open circle), and low-S/N (light gray dot); see § 2.4.1 for the detail on Na\textsc{i} D kinematics. Outflows/inflow data points are color-mapped with the blueshift probability (§ 2.4.1), where bluer (redder) marks indicate stronger blueshift (redshift) of Na\textsc{i} D absorption line. The green lines are the loci of Na\textsc{i} D indices measured in the simulated DEEP2 spectra assuming fiducial Na\textsc{i} D absorption profiles expected from the fixed optical depth and covering fraction (τ = 1.1 and C\textsubscript{f} = 0.4) at three different Doppler widths [b\textsubscript{D} = 50 (dotted green line), 150 (dashed green line), and 350 km s\textsuperscript{-1} (dash-dotted green line)], which are varied to simulate the effect of broadening in the absorption profile (not convolved with the instrumental resolution of ≈ 42 km s\textsuperscript{-1} here); see the Appendix for the definitions of the variables. The model with b\textsubscript{D} = 150 km s\textsuperscript{-1} roughly reflects the mean Na\textsc{i} D property of LIRGs reported by Rupke et al. (2005b); i.e., the long dashed line in the upper panel indicates the significance of detection for a typical LIRG wind. For each model, a number of realizations are generated at a given S/N (i.e., a spectrum is degraded by Gaussian noise assuming that S/N), and the measurements on them yield the uncertainty in the spectral index. [See the electronic edition of the paper for a color version of this figure.]

![Graph showing Median S/N per pixel near Na\textsc{i} D](image)

**Fig. 3.**—Distribution of Na\textsc{i} D velocity confidence intervals as a function of continuum (S/N)\textsubscript{pix} around Na\textsc{i} D. Here Δv\textsubscript{68%} is the difference of upper and lower 68% confidence limits in Na\textsc{i} D velocity. The symbols are as in Fig. 2. Inset: The Na\textsc{i} D velocity measurement with the error bar indicating the 68% confidence interval as a function of blueshift probability p\textsubscript{blue}. Outflows and inflows from the high-S/N sample are color-coded by blue and red, respectively, in gradient according to p\textsubscript{blue} (§ 2.5); those at the systemic velocity are in gray. The low-S/N velocity sample (§ 2.4.1) are in light gray. High- and low-S/N velocity measurements are effectively separated in the ways that they are distributed in these plots, indicating the efficacy of the visual inspection scheme; see the text for detail. [See the electronic edition of the paper for a color version of this figure.]

Each Na\textsc{i} D central wavelength λ\textsubscript{c} is converted to the Na\textsc{i} D velocity offset

$$\nu(\text{Na}\textsc{i} \text{ D}) = c \frac{\lambda\textsubscript{c} - \lambda\textsubscript{sys}}{\lambda\textsubscript{sys}},$$

where c is the speed of light and λ\textsubscript{sys} = 5895.2943(1 + z) Å is the line center of Na\textsc{i} D shifted to the observed frame using the cross-correlation redshift z. (The redder line of the doublet, Na\textsc{i} λ 5896, is used as the reference line throughout.) Using the above equation, the probability distribution of ν(ν(\text{Na}\textsc{i} D) is directly obtained from the probability distribution of λ\textsubscript{c} from the MCMC sampling for each spectrum. In order to take into account the systemic redshift uncertainty, the probability distribution is further convolved by a Gaussian kernel having a width corresponding to the 1\σ uncertainty in the cross-correlation redshift (in the velocity space) for each object. From each probability distribution, the best estimate for Na\textsc{i} D velocity is taken from the median, and the 68% confidence interval is likewise obtained.

For the purpose of measuring the Na\textsc{i} D velocity, the absorption feature detected at a sufficient S/N for such a measurement generally reveals itself as a normally distributed probability density in ν(ν(\text{Na}\textsc{i} D) well within the boundaries within which the parameter is varied, ν(ν(\text{Na}\textsc{i} D) = ±700 km s\textsuperscript{-1}.\textsuperscript{11} At a lower S/N, a probability distribution

\textsuperscript{11}While the Na\textsc{i} D outflow velocities above and below the allowed interval have been reported in literature (e.g., Rupke et al. 2005b; Martin 2005), the visual inspection of the velocity measurements indicates that the range of ±700 km s\textsuperscript{-1} is sufficient for our sample, which does not include ULIRGs (with signs of AGN activities) in which the most very high velocity outflows are observed.
for $v(\text{Na} \, \text{I} \, \text{D})$ starts exhibiting the high and low velocity tails toward these values at the boundaries. Hence, after visual inspection, we divide our $v(\text{Na} \, \text{I} \, \text{D})$ measurements into two classes based on the behavior of $v(\text{Na} \, \text{I} \, \text{D})$ probability distribution: “high-S/N” velocity sample ($N = 205$) for the distribution is well within $\pm 700 \, \text{km} \, \text{s}^{-1}$ and “low-S/N” velocity sample ($N = 226$) for which the distribution either extends to the boundary or is ill-behaving. Visual inspection also guards against the sampling results latching on to unwanted noise features, which usually show up as an abnormal probability distribution function. The MCMC measurement pipeline also allows a fitted absorption-line profile to be inspected for an interactively-picked set of model parameters, so the integrity of the fitting result has also been visually checked at various points in the distributions of model parameters; see the Appendix for detail. Fig. 3 shows the velocity width of confidence intervals ($\Delta v_{68\%}$; i.e., the difference between the upper and lower $68\%$ confidence intervals) as a function of $\text{Na} \, \text{I} \, \text{D}$ velocity, are shown in Fig. 4 for the cases of $p_{\text{blue}} \simeq 1$ (certainly an outflow), 0.5 (likely at systemic), and 0.01 (almost certainly “inflow”). The value of $p_{\text{blue}}$ is a measure of how likely that a “real” $\text{Na} \, \text{I} \, \text{D}$ velocity is blueshifted from the systemic velocity, given the result of MCMC sampling and the uncertainty in the systemic redshift of host galaxy.

2.5. Definition of Outflow

To define what constitutes an outflow (“inflow”) detection for the current analysis, we use a $\text{Na} \, \text{I} \, \text{D}$ velocity cut of $v(\text{Na} \, \text{I} \, \text{D}) < -50 \, \text{km} \, \text{s}^{-1}$ ($> +50 \, \text{km} \, \text{s}^{-1}$) and a blueshift probability cut of $p_{\text{blue}} > 0.75$ ($< 0.25$). Although a blueshift probability could be an adequate indicator of the likelihood of detecting an in/outflow at a desired confidence level, the additional velocity cutoff is used to guard against both the random and systematic errors in the redshift and the velocity measurements. The specific choice for the velocity cutoff is primarily motivated by the typical $v(\text{Na} \, \text{I} \, \text{D})$ uncertainty of $\sim 50 \, \text{km} \, \text{s}^{-1}$ (Fig. 3) and the visual inspection of fitting results in view of $v(\text{Na} \, \text{I} \, \text{D})$ and $p_{\text{blue}}$. Most importantly, when the width of probability distribution function is narrow (i.e., $\Delta v_{68\%}$ is small), the value of $p_{\text{blue}}$ becomes very sensitive to the particular value of the systemic velocity; that is, convolving a distribution function obtained from an MCMC analysis with a redshift measurement uncertainty ($\Delta z_{\text{sys}}$) may not adequately account for the error in a single measurement of systemic redshift. While employing a more stringent $p_{\text{blue}}$ cut would yield a sample of outflows detected with higher confidence, we then have to compromise our sample size. Given the limited S/N, we opt to look at a sample that is constructed statistically and systematically, rather than look for very secure outflow/inflow detections. The similar velocity cutoff was employed by Rupke et al. (2005b) to define outflow. Readers are cautioned that, based on instrumental effects and data quality, the precise definitions of outflow necessarily vary in the literature.

As emphasized earlier, one caveat of the $\text{Na} \, \text{I} \, \text{D}$ absorption analysis in this paper is our inability to remove the stellar contribution in the $\text{Na} \, \text{I} \, \text{D}$ absorption ($\Delta v_{68\%}$); a stellar fraction can only be estimated indirectly from such an index as $\text{Mg} \, \text{I} \, \text{b}$ whose strength is known to correlate well with that of $\text{Na} \, \text{I} \, \text{D}$. Since the presence of interstellar absorbers is a necessary condition for outflows seen in absorption, some trend is expected to exist between the outflow detection rate and the interstellar fraction of the total $\text{Na} \, \text{I}$ column. Fig. 5 shows that such a trend does exist, in which the objects with low $\text{Na} \, \text{I} \, \text{D}$ stellar absorption fractions are more likely to host outflows (that we can detect). Without the explicit removal of stellar absorption components, however, the figure does not necessarily imply the paucity of outflows in galaxies whose $\text{Na} \, \text{I} \, \text{D}$ is dominated by the stellar contribution. It is important to note again that our census is only sensitive to fairly strong outflows of the kind expected in LIRGs (Fig. 2). Furthermore, since only one
Na I D doublet component is fitted, the measured Na I D velocities are likely the lower limits to the kinematic component with the highest outflow velocity; each Na I D velocity is sensitive to the "moment" of multiple absorption components, at least one of which is stellar in origin and therefore appears at the systemic redshift. In high-S/N spectroscopy of (U)LIRGs, Rupke et al. (2005a) and Martin (2005), for example, could fit more than one component of Na I D absorption in some spectra, provided that line profiles are not overly "smooth" due to blending and instrumental smearing. The kind of weak outflows observed by Schwartz & Martin (2004) in dwarf starbursts is certainly below the detection level of the present survey. Our velocity measurements appear sensitive to outflows in Na I D when \( \gtrsim 50\% \) of the absorption equivalent width is interstellar in origin. Given these limitations, attaching a physical meaning to a Na I D velocity would be misleading, since it is only the shift in the moment of the absorption profile, not the isolated absorption from the outflowing/inflowing gas, to which our measurements are really sensitive. We thus avoid emphasis on the exact Na I D velocity values.

2.5.1. Reality of "Inflows"

The sensible cuts in the Na I D velocity and blueshift probability \( P_{\text{blue}} \) give rise to a population of galaxies with "inflows." While it would not be surprising to see an inflow from a sightline through an interacting system, "inflows" in our sample are seen mostly in luminous, massive galaxies in the red sequence (Fig. 10 and Fig. 15). The presence of inflows in these objects is striking. Given that these "inflow" detections are almost exclusively in early-type galaxies with relatively little interstellar gas, it is possible that some unaccounted spectral features may be causing systematics.

One possibility is the presence of some unaccounted metal absorption lines redward of Na I D, systematically redshifting the Na I D profile fit; the experimentation with synthesis spectra from Bruzual & Charlot (2003) and Delgado et al. (2005) indicates that the degree of systematics would not be as strong as observed, assuming Na I D is properly modelled. Another source of systematics may be the cross-correlation redshift measurement. The precision of cross-correlation redshifts is generally worse with templates dominated by absorption lines, from which the redshifts of galaxies with "inflows" are obtained. It is also difficult to visually inspect redshift systematics in absorption-dominated spectra due to the lack of narrow, high-S/N features. As mentioned in § 2.2, a systematic velocity difference of order 10 km s\(^{-1}\) also exists between cross-correlation and DEEP2 redshifts but is small compared to the velocities of inflows. We do, however, sufficiently take the redshift uncertainty into account in our definition of inflows (§ 2.4.1). Furthermore, as a significant fraction of galaxies with "inflows" appear to have lenticular morphology (Tremonti et al., private communication), another possibility is that a distinct kinematic component of stellar motion might be detected in these systems, perhaps from a faint disk.

While some of the above listed concerns are equally valid for outflows, in following sections we show compelling evidence that the detections of outflows are physically associated to star formation. Such a clear physical connection cannot be made for inflows at present, and a preliminary investigation to explore the nature of the "inflow" population is underway. In radio ellipticals, neutral hydrogen is often seen in inflow, plausibly feeding the nuclear activity (e.g., van Gorkom et al. 1989). If our inflows are indeed associated with the feeding of AGNs, our measurements could provide an effective means of identifying the massive, early-type galaxies going through the maintenance-mode of AGN feedback. Nonetheless, we delay such a discussion of inflows to future papers.

2.6. On Selection Effects

Dependence on Na I D absorption strength. Our ability to measure a Na I D velocity depends primarily on the combination of the absorption and the continuum strengths, which introduces selection biases. Our main selection cut on continuum S/N around Na I D feature favors luminous, high surface brightness objects, which tend to be early-type galaxies on the red sequence (Fig. 10). Star-forming galaxies in the blue cloud are much fainter at \( z < 0.5 \) from which our sample is drawn. Furthermore, velocity measurements are better behaving for stronger Na I D absorption. In Fig. 1, we see that high \( W_0(\text{Na} \text{ I} D) \) objects tend to be old galaxies with a high stellar fraction or young galaxies with a high interstellar fraction in their Na I D absorption. Our survey lacks sensitivity to absorption lines in less luminous star-forming galaxies, where much of star formation occurs at \( z < 0.5 \). Therefore, that a significant fraction of our outflow detections is in redsequence galaxies is partially a selection effect. Nonetheless, our sample nicely complements the existing studies of Na I D outflows which have focused on starburst galaxies.

Redshift dependence. Our sample consists of objects distributed over a fairly large redshift interval of 0.11 < \( z < 0.54 \), and the analysis suffers from the problem typically encountered by a flux-limited survey. First, the observation becomes increasingly insensitive to fainter populations at higher redshift. Second, given a fixed opening angle, the survey volume...

![Graph](image-url)
Fig. 6.— The stellar mass as a function of redshift for the sample in this study. Each galaxy is coded by the Na I D kinematics (Fig. 3): outflow (blue filled circle), systemic (gray cross), inflow (red open circle), and low-S/N (light gray dot). The horizontal dashed lines indicate the 95% completeness limit in stellar mass computed at the centers of redshift intervals for $0.2 < z < 0.45$ and $0.45 < z < 0.7$ from Noeske et al. (2007a). The green dotted curve indicates the quenching mass limit as presented in Bundy et al. (2007). [See the electronic edition of the paper for a color version of this figure.]

Insight into these effects are gained from Fig. 6. Apparently, the high-S/N sample does not reach the completeness limit in stellar mass of the parent AEGIS survey, except at the lowest redshifts. The lower sampling rate of high-mass galaxies [e.g., $\log (M_*/M_\odot) \geq 11$] at low redshift may be a result of the smaller survey volume; that is, luminous early-type galaxies tend to be highly clustered (e.g., Coil et al. 2007), and a smaller number of overdense regions with bright ellipticals fall in the field of view toward lower redshift. The effect of the changing physical aperture size, from 2 kpc to 9.5 kpc corresponding to the $IV$-slit, on the detectability of outflow is difficult to assess. The work by Martin (2006) on the spatially-resolved Na I D outflows in local ULIRGs indicates that the extended blueshifted interstellar absorption is found over the scale of $\gtrsim 15$ kpc, in which case a significant column should remain available.

3. HOST GALAXIES OF OUTFLOWS

3.1. Trends with Star Formation

Since the recent advance in the detailed knowledge of starburst-driven galactic winds have been gained through the studies of local LIRGs (e.g., Heckman et al. 2000; Rupke et al. 2002, 2005a,b; Martin 2005), the Na I D velocity measurements as a function of infrared luminosities $L_{IR}$ naturally provide a starting point for comparison. Since for star-forming galaxies the infrared is dominated by the thermal dust emission of reprocessed starlight from hot, young massive stars, a tight correlation exists between $L_{IR}$ and SFR in dusty star-forming galaxies (Kennicutt 1998). For a subset of our sample, the far-infrared photometry from Spitzer/MIPS (Rieke et al. 2004) are used to derive the total infrared luminosity $L_{IR}$, following Le Floc’h et al. (2005) and using the Chary & Elbaz (2001) SED templates. In Fig. 7, a clear tendency is observed for high $L_{IR}$ objects to host outflows. Indeed, a majority of outflows are found in LIRGs ($L_{IR} > 10^{11} L_\odot$) in the figure. Table 2 presents the outflow detection rates for the subsampling based on $L_{IR}$. The outflow detection rate of $38 \pm 11$% for LIRGs is similar to those reported by low-$z$ surveys of infrared-selected galaxies; e.g., 42 $\pm$ 8% in Rupke et al. (2005b) and 32 $\pm$ 12% in Heckman et al. (2000). Hence we confirm the results reported by others that the detection rate of outflow in infrared-selected galaxies correlates well with their infrared luminosity. We note, however, that the exact values for the detection rates, especially among the galaxies with lower SFRs, may not be robust against selection effects and incompleteness, since our primary selection cut is made by the strength of continuum around Na I D ($\geq 2.3$). There are no ULIRGs [$\log (L_{IR}/L_\odot) > 12$] in our sample, which is reasonable given the expected number of ULIRGs in the survey volume is very small ($\lesssim 10$), assuming redshift-dependent lu-

![Graph showing stellar mass as a function of redshift](image-url)

![Graph showing Na I D velocity as a function of $L_{IR}/L_\odot$](image-url)

Table 2: Detection Rates for Na I D Outflows Selected by $L_{IR}$

<table>
<thead>
<tr>
<th>Criterion</th>
<th>$N_{\text{subsample}}$</th>
<th>$N_{\text{outflow}}$</th>
<th>Detection Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>With MIPS observation</td>
<td>169</td>
<td>24</td>
<td>0.14 $\pm$ 0.03</td>
</tr>
<tr>
<td>$\log (L_{IR}/L_\odot) &gt; 11$</td>
<td>21</td>
<td>8</td>
<td>0.38 $\pm$ 0.11</td>
</tr>
<tr>
<td>$\log (L_{IR}/L_\odot) \leq 11$</td>
<td>148</td>
<td>16</td>
<td>0.11 $\pm$ 0.03</td>
</tr>
</tbody>
</table>

Note. — The conventional cut for LIRGs is $\log (L_{IR}/L_\odot) > 11$. Only the objects with high-S/N Na I D velocities are included for the calculation of detection rates; i.e., the objects in the low-S/N sample (§ 2.4.1) are treated as if they are not detected. The uncertainties are estimated from binomial statistics.
minority functions of infrared sources (Le Floc’h et al. 2005) and the completeness of the DEEP2 survey.

In Fig. 8, the Na I D velocity as a function of the total SFR [i.e., the sum of SFRs derived from infrared SED and optical emission lines; see Noeske et al. (2007a) for detail] is shown. The similar dependence of v(Na I D) on $L_{IR}$ and the total SFR is due to the tight correlation between $L_{IR}$ and the total SFR, which is often dominated by the infrared contribution. Again, a majority of outflows are seen in galaxies with SFR $\gtrsim 20 M_\odot$ yr$^{-1}$, which correspond to the amount of SFR expected in LIRGs. As a caveat, it should be mentioned that part or even much of the infrared luminosity might be from (obscured) infrared-bright AGN, and not from star formation. We lack the diagnostics to distinguish star formation from AGN, but the simple relation between $L_{IR}$ and SFR may not hold for the cases in which AGN contributions to the infrared luminosities are high.

Since the SFR scales almost proportionally with galaxy mass (e.g., Brinchmann et al. 2004), its inference with respect to the specific amount of star-forming activity may be misleading. The birthrate parameter, $b \equiv SFR/(SFR)$ (Kennicutt 1998), is a better indicator which takes into account the star formation history yet is difficult to estimate due to its dependence on the time scale over which the galaxy has been forming stars as well as the fraction of gas recycled in the past. It is still desirable to remove the first-order effect of galaxy mass, since our sample is drawn over the redshift interval where downsizing affects star formation particularly strongly. Specific SFR, defined as $SFR/M_*$ (i.e., SFR per unit stellar mass), however, is a reasonable proxy for birthrate parameter. Fig. 9 shows how the specific SFRs are distributed as a function of galaxy stellar mass $M_*$, obtained from fitting SEDs to optical and near-infrared photometry (Bundy et al. 2006). In the figure, most objects with log(SFR/$M_*$) $\lesssim -10$ are in the red-sequence (Fig. 10), so their specific SFR may be overestimated due to LINER/AGN contamination (Yan et al. 2006; Weiner et al. 2007). Focusing on the region in which log(SFR/$M_*$) $\gtrsim -10$, an interesting feature is that, at a fixed mass, most objects with outflows are seen at the upper envelope of the distribution of specific SFRs. The analysis of the parent AEGIS sample by Noeske et al. (2007a,b) indicates that, in the redshift interval 0.11 $\lesssim z \lesssim 0.55$ from which our sample is drawn, $M_* \sim 10^{11} M_\odot$ is roughly where star formation is seen to be quenched in the most massive galaxies. In the full Noeske et al. (2007b) sample, the distribution of star-forming galaxies is fairly tight; the loci in Fig. 9 suggest that host galaxies of outflows are undergoing an enhanced episode of star formation, relative to the star-forming galaxies without outflows at the same epoch.

### 3.2. Color-Magnitude Diagram

Although optical photometry only tells an incomplete history, dividing galaxies into blue and red populations by optical colors still is very useful for capturing the essence of galaxy evolution with a bird’s-eye view, since the bimodality of galaxy color distribution is among the most prominent features that persist over wide ranges of parameters, such as galaxy mass, luminosity, environment, and redshift (e.g., Baldry et al. 2004; Balogh et al. 2004; Willmer et al. 2006; Cooper et al. 2007). Over the past few decades, numerous studies of local galaxies have shown that the “red sequence” is generally populated by red, dead, passively evolving galaxies with old stellar populations, while the “blue cloud” is populated by blue, actively star-forming galaxies. These two densely-populated regions are divided by a sparsely-populated area, sometimes called the “green valley”; see Faber et al. (2007) and references therein for a more comprehensive account.

Fig. 10 presents the rest-frame $(U-B, M_B)$ color-magnitude diagram, in which the host galaxies of outflows are seen in relation to the red sequence and the blue cloud, where the catalog of rest-frame photometry was constructed as described in
Willmer et al. (2006).\textsuperscript{12} Given that the low-\(z\) red sequence galaxies are characterized as inactive and quiescent, that a majority of outflows are found in red galaxies comes as a surprise; among 32 outflows, 21 of them are found on the red sequence. Non-star-forming, quiescent galaxies are red in the rest-frame optical due to their SEDs; the rest-frame \(U - B\) in particular brackets the 4000 \(\AA\) feature, which is sensitive to the “break” caused by the Balmer limit, as well as the high metal opacity in the cool stellar atmosphere of old stars. Nonetheless, the dust reddening can push some star-forming galaxies into the red sequence, especially at higher redshift (e.g., Weiner et al. 2005; Bell et al. 2005). The rest-frame photometry in Fig. 10 are not corrected for the internal extinction of galaxies, so the “contamination” from dust-reddened star-forming galaxies could be significant though expected to be small at \(z < 0.5\). We also reiterate that, due to the fixed continuum S/N cut, our sample is naturally biased for red-sequence galaxies, which tend to have high surface brightness (§ 2.3).

Fig. 11 shows the color-magnitude diagram in which the objects are denoted by their infrared luminosity and offers evidence that a significant number of star-forming galaxies do reside in the red sequence. The sample is divided at \(z = 0.35\) into low and high redshift subsamples, which makes clear that the infrared-luminous galaxy fraction is much greater at higher redshift, consistent with lookback-time studies of star-forming, infrared-luminous galaxies (e.g., Bell et al. 2005; Le Floc’h et al. 2005; Noeske et al. 2007a). A comparison of the top and bottom panels shows quite strikingly that the \(z > 0.35\) red sequence has a substantial number of infrared-luminous galaxies, some of which are LIRGs, which is absent in the \(z < 0.35\) red sequence. Outflows are mostly observed in \(z > 0.35\) objects. The red-sequence outflows, however, are found in the objects with moderate to high \(L_{\text{IR}}\), as well as those without significant 24 \(\mu\)m flux. This shows that outflows can exist in either star-forming or non–star-forming objects.

While the narrow spectral baseline of DEEP2 makes the Balmer decrement unavailable, the UV spectral slopes \(\beta\) from

\[ \text{Fig. 10.— Rest-frame} \ (U - B) - M_B \text{ color-magnitude diagram. The photometry, on the Vega system, is corrected for Galactic extinction but not for the internal extinction of galaxies; see Willmer et al. (2006) for detail. The symbols are as in Fig. 2. The dashed line indicates the} \ U - B \text{ color cut used to divide red-sequence and blue-cloud galaxies; see Faber et al. (2007). [See the electronic edition of the paper for a color version of this figure.]} \]

\[ \text{Fig. 11.— Rest-frame} \ (U - B) - M_B \text{ color-magnitude diagram for objects at} \ z \geq 0.35 \text{ (top) and} \ z < 0.35 \text{ (bottom). The gray dashed lines divide red and blue galaxies (Fig. 10). The symbol indicates the infrared luminosity} L_{\text{IR}}; \text{below flux limit} (\text{dot}), \log (L_{\text{IR}}/L_\odot) \leq 10.5 \text{ (cross),} \ 10.5 < \log (L_{\text{IR}}/L_\odot) \leq 11 \text{ (open circle), and} \log (L_{\text{IR}}/L_\odot) > 11 \text{ (open square). The color scheme for the symbols is similar to Fig. 2 and indicates Na I D kinematics:} \text{outflow} \text{ (blue), inflow} \text{ (red), systemic} \text{ (gray), and low S/N (light gray). There are roughly equal number of objects above and below the redshift cut at} \ z = 0.35. \text{ [See the electronic edition of the paper for a color version of this figure.]} \]

\[ \text{Fig. 12.— Rest-frame} \ U - B \text{ color as a function of the UV spectral slope} \ \beta \text{ for a subset of objects with GALEX photometry. The} \beta \text{ follows the definition given by Seibert et al. (2005),} f_\beta \propto \lambda^2; \text{ a more reddened spectrum has a smaller value of} \ \beta. \text{ The symbols are as in Fig. 2. A majority of blue-sequence galaxies are classified as low-S/N; they are bright in UV but fainter in the visible, making it difficult to obtain their high-S/N spectra. [See the electronic edition of the paper for a color version of this figure.]} \]

\[ \text{\textsuperscript{12} The optical photometry are on the Vega system. See Willmer et al. (2006) for the conversion procedure between Vega and AB magnitudes.} \]

\[ \text{found in the objects with moderate to high} L_{\text{IR}}, \text{ as well as those without significant 24 \(\mu\)m flux. This shows that outflows can exist in either star-forming or non–star-forming objects.} \]
These results give rise to an interpretation that the arrival on the red sequence of the galaxies with outflows happened only recently; i.e., the red-sequence outflows are found predominantly in post–star-forming galaxies with detectable residual star formation. The redness in their visible colors might also arise partly from the presence of dust; the strong correlation between reddening $E(B - V)$ and the equivalent width of low-ionization absorption lines are often reported (e.g., Armus et al. 1989; Veilleux et al. 1995; Heckman et al. 2000). Poststarburst galaxies, identified spectroscopically by their strong Balmer absorption, are generally found to be dusty as well (e.g., Poggianti & Wu 2000; Poggianti et al. 2001; Balogh et al. 2005; Sato & Martin 2006). The appearance of the post–star-forming phase also fits well with the scenario that it is observed when star-forming galaxies in the blue cloud make the transition to the red-sequence after some mechanism triggered an enhanced episode of star formation, which then gets shut off. The $NUV - R_{AB}$ color alone, however, does not rule out low-level star formation in these galaxies, since whether a galaxy goes through poststarburst depends on the fraction of mass that has formed in the most recent star formation event as well as its timescale. It is also worth noting the clear separation between outflows and inflows in $NUV - R_{AB}$; most inflows are observed in red galaxies in which little or no star formation is detected.

3.3. Evidence for Poststarburst

The Balmer absorption lines are sensitive to the age of the underlying stellar population and become prominent in the spectrum in which A to early-F stars, living up to 1 Gyr, contribute significantly. This feature has been exploited to find the signature of poststarbursts in distant galaxies, often using $H\delta$ and/or $H\gamma$ absorption due to less contamination from emission filling (e.g., Dressler & Gunn 1983; Zablud-
off et al. 1996; Dressler et al. 2004; Goto 2007). The limited spectral baseline makes only low-lying Balmer lines available for our sample. Fig. 14 shows the Na\textsc{i} D velocity as a function of the H\textbeta spectral line index \( W_{0}(\text{H}\beta) \). A spectral line index is an estimate of the sum of emission and absorption equivalent widths (§2.2.1). In the figure, outflows are seen in two following classes of objects. One class is those with \( W_{0}(\text{H}\beta) < 0 \) Å, meaning that H\textbeta is seen in emission, so they are the outflows seen in star-forming galaxies in the blue cloud (Fig. 10). Another is those with \( W_{0}(\text{H}\beta) \gtrsim 3 \) Å, slightly offset from a concentration of objects with systemic Na\textsc{i} D velocity around \( W_{0}(\text{H}\beta) \approx 2 \) Å. To put this in perspective, the inset of Fig. 14 shows the evolution of stellar H\textbeta absorption index over a range of stellar ages. A stellar population with the age \( \gtrsim 10 \) Gyr has its \( W_{\star}(\text{H}\beta) \) asymptotically to \( \approx 2 \) Å. The H\textbeta absorption would be seen at \( W_{0}(\text{H}\beta) \gtrsim 3 \) Å during the poststarburst phase from 10 Myr to \( \sim 2 \) Gyr. In practice, a measured H\textbeta index from a galaxy spectrum includes the nebular emission line flux originating from the H\textalpha regions surrounding hot, young stars; at \( \lesssim 100 \) Myr, the H\textbeta index would be seen in emission [i.e., \( W_{0}(\text{H}\beta) \lesssim 0 \) Å]. Therefore, \( W_{0}(\text{H}\beta) \gtrsim 3 \) Å objects are likely to be in the poststarburst phase. A large number of systemic Na\textsc{i} D velocity objects around \( W_{0}(\text{H}\beta) \approx 2 \) Å is also consistent with old, quiescent galaxies not hosting outflows.

The bottom panel of Fig. 13 shows the relation between the NUV\textminus R\textsc{ab} color and the H\textbeta spectral line index for the subset of sample with both measurements. Although the small statistics makes interpretation difficult, we can see that the red-sequence objects with outflows appear to have a slightly higher \( W_{0}(\text{H}\beta) \) in general compared to those without. Some blue-sequence objects with NUV\textminus R\textsc{ab} \( < 5.4 \) also move to the \( W_{0}(\text{H}\beta) > 0 \) Å regime. If these objects are of poststarburst type, the residual star formation, inferred from their blue NUV\textminus R\textsc{ab} color, may contribute a small emission flux to H\textbeta absorption, making the observed \( W_{0}(\text{H}\beta) \approx 2–3 \) Å only lower limits to their absorption equivalent strength. This makes the case stronger for the poststarburst identity.

The combination of selection cuts from our sample yields a small number of fully overlapping objects across a variety of measurements and makes it difficult to reach generalizing conclusions with statistical rigor. Nevertheless we do find overwhelming consistency in the evidence that our LIRG-type outflows are mostly seen either in starburst or poststarburst objects. This naturally fits into the currently favored scenario of galaxy evolution between blue-cloud and red-sequence galaxies, in which some mechanism (e.g., merger) triggers a starburst in a blue galaxy which then gets “quenched” by some feedback mechanism, such as by an AGN or supernovae, by the time the galaxy joins the red sequence. The outflows may be the result of such feedback process observed in “transition” objects.

However, we must also note that stronger Balmer absorption only indicates that there was certainly a detectable enhancement, relative to the present, of star formation in the recent past; whether or not an individual case makes the criteria for a conventional starburst is admittedly unclear, especially given our crude diagnostics. There are plausible ways for galaxies to quench star formation without going through a starburst phase, and such mechanisms could generate outflows and detectable enhancement of Balmer absorption, if quenching occurs quickly. That possibility can be explored further only through better diagnostics.

### 3.4. Host Morphology

Fig. 15 shows a subset of galaxies with Na\textsc{i} D measurements for which we have the quantitative morphology from the HST/ACS imaging analysis by Lotz et al. (2006). A set
of new nonparametric morphology measures, Gini coefficient $G$ which measures the distribution of flux among pixels over a galaxy and the second-order moment of the brightest 20% of the total galaxy flux $M_{20}$, is calibrated visually to the traditional morphological classifications (Lotz et al. 2004): early-type (E/S0/Sa), late-type (Sb–Irr), and merger candidates. Our survey is more sensitive to luminous, high surface brightness galaxies (§ 2.3), and Fig. 15 shows that the sampling is biased against objects with late-type (i.e., lower surface brightness) morphology; see Lotz et al. (2006) for the analysis of complete samples drawn from the parent AEGIS survey, which shows that the many objects with low surface brightness, late-type morphology, which would appear toward the bottom left corner, did not make our selection cut.

A high fraction (3/6 = 0.5 ± 0.2) of merger candidates are host to outflows, although the sample is admittedly very small. Lotz et al. (2004) showed that their morphological classification effectively identify nearby ULIRGs as mergers. Most local ULIRGs are known to be associated with some sort of interaction (e.g., Murphy et al. 1996; Borne et al. 2000; Cui et al. 2001). None of our objects are ULIRGs, and, although all three merger candidates with outflows are detected at 24 μm, only one is a LIRG. Since the dynamical timescale of merger, $\sim 1$ Gyr, exceeds that of gas consumption, $\sim 100$ Myr, it is likely that we miss the ULIRG phase due to its short duty cycle. Nonetheless, outflows are detected in almost all ULIRGs (Martin 2005, 2006; Rupke et al. 2005b), and the strongest winds appear to be seen near the perigalactic passage Martin (2005). Since the transition from a LIRG to a ULIRG (which eventually may become a quasar) may be physically plausible in the merger sequence (Sanders 2004), the high outflow detection rate in merger candidates is not surprising. It should be noted, however, the nature of the association between mergers/interactions and (UL)IRLGs is not very clear for objects at $z \sim 0.5$.

A majority (9/14) of outflows are seen in the objects with early-type morphology (E/S0/Sa). An insight to the order of morphological transformation may be given by Fig. 16, which plots the distribution of morphology in terms of the rest-frame ($U-B$, $NUV-R_{AB}$) color-color diagram. Consistent with the common knowledge, most late-type galaxies are in the blue cloud, while most early-type galaxies are in the red sequence. The distribution of outflow hosts follows a similar trend. Although the small sample size does not allow to make a statistically robust conclusion, outflows appear to be seen more preferentially where merger candidates are also seen. We find evidence that outflows are often seen in poststarburst objects (§ 3.3), and their early-type morphology, coupled with the signs of interaction in a few of them, is consistent with the existing studies of poststarburst galaxies, which conclude that they are spheroidal, often showing the sign of interaction (e.g., Yang et al. 2004; Goto 2005).

The two outflow objects with late-type morphology are at $z > 0.35$ and have infrared luminosities $\log (L_{IR}/L_{\odot}) \approx 11.1$ and 10.4. Unlike ULIRGs, the morphology of LIRGs appears to be a mixed bag. At $z \sim 0.7$, however, more than half of their LIRGs have disk morphology (e.g., Bell et al. 2005; Melbourne et al. 2005), suggesting that the abundant LIRG population simply reflects an elevated level of star formation in normal galaxies at an earlier lookback time. All our objects are at lower redshift, yet it is possible that we might have caught a couple of them. In general, however, our selection is highly biased toward high surface brightness galaxies; it is likely that we have missed the population of low surface brightness star-forming galaxies that appear dim in the rest-frame visible continuum, with which our selection cut has been made.

4. DISCUSSION

We have seen that the detection rate of LIRG-like outflows is a strong function of infrared luminosity or star formation rate (§ 3.1). The distribution of specific star formation rates at a fixed stellar mass (Fig. 9) might imply that the frequency of outflows may be higher for the objects in which ongoing star-forming activity is enhanced relative to the past average (i.e., high birthrate parameter). The distribution in the optical color magnitude diagram shows that outflows are abundant both in the blue cloud and the red sequence (§ 3.2). The NUV photometry reveals that the red-sequence outflows are hosted by the objects that have gone through recent star formation (Fig. 13). There are evidence that some of the red-sequence outflows are in dusty (Fig. 12), star-forming galaxies (Fig. 11). Yet some may be poststarburst galaxies (§ 3.3) just arriving the red sequence, which is consistent with their early-type morphology (§ 3.4). We now discuss a few fine points that need attention, and describe how our finding of Na I D outflows may fit into the current understanding of galaxy formation and evolution.

4.1. Redshift Evolution of Outflows

Fig. 6 shows the detection of outflows as a function of redshift in our sample. Over the redshift range, star-forming properties of galaxies are expected to change and so do the detection rates of outflows. In the figure, no $M_*$ $\approx 10^{11} M_{\odot}$ galaxies at $z \approx 0.2$ show signs of an outflow, yet a significant fraction of galaxies with the similar mass at $z \approx 0.5$ do. This is consistent with the known trend of the star formation history of galaxies and the increasing trend of outflow detection rate with SFR (§ 3.1); Noeske et al. (2007a) shows that star-forming galaxies with $M_* \approx 10^{11} M_{\odot}$ are rare at $z < 0.45$ but are abundant and most are LIRGs at $z > 0.45$. Fig. 6 shows that the outflows detected in our sample are typically seen in high-$M_*$ galaxies at higher $z$ with a SFR expected in a LIRG ($\geq 20 M_\odot yr^{-1}$). Due to low S/N, however, we cannot say whether or not lower-$M_*$ galaxies at $z \sim 0.5$ host outflows. Nevertheless, at the high $M_*$ end, we clearly observe that the “downsizing” effect extends to the detection rate of LIRG-like outflows, i.e., the typical mass of galaxies that host outflows move to a lower mass toward lower redshift, much like the trend seen in cosmic star formation history of galaxies (e.g., Madau et al. 1996; Lilly et al. 1996; Le Floc'h et al. 2005; Faber et al. 2007; Noeske et al. 2007a; Cooper et al. 2007). Bundy et al. (2006) quantifies the evolving trend in terms of the “quenching mass limit,” which is shown in Fig. 6 for a crude comparison.

4.2. Merger-triggered Activities and Outflows

Merger-driven galaxy evolution has been a prominent paradigm over the past decades, and the current success of the ΛCDM theory in describing the hierarchical structure formation certainly points to its significant roles in galaxy-scale phenomena. The relevance of mergers in shaping the cosmic star formation history of galaxies, however, is under intense scrutiny. The difficulty arises from the fact that direct identification of mergers and quantifying their frequency from the observation of high redshift galaxies remains very challenging, due to a number of factors including surface brightness dimming and shifting passbands. Galaxy mergers of
star-forming disk galaxies have attracted much attention, because they are a mechanism widely known to cause enhanced star formation, after which merger remnants dynamically relax into spheroids (e.g., Mihos & Hernquist 1996; Cox et al. 2006). Along with the expected increase of the merger rate with the lookback time from numerical simulations (e.g., Gottlöber et al. 2001), mergers have been invoked as a mechanism responsible for the declining trend of the comoving star formation density since \( z \sim 2 \) (e.g., Lilly et al. 1996; Madau et al. 1996), although exactly how much mergers contribute to the trend is still debated (e.g., Bridge et al. 2007; Lotz et al. 2006). Galaxy merger is appealing also for it affects star-forming as well as morphological properties of galaxies in ways that naturally explain the observed transition of young (i.e., blue and disky) into old (i.e., red and spheroidal) galaxy populations. In principle, a variety of such transient phenomena as starburst and quasars can also be integrated into a coherent picture of merger-driven galaxy evolution (e.g., Sanders & Mirabel 1996; Hopkins et al. 2006).

The correlation of the outflow detection rate with the degree of elevation in star-forming activity certainly indicates that starbursts are an important component of galactic superwind phenomenon. However, outflow is exciting not because it is associated to such a spectacular starburst event, but because it may carry away from the host galaxy the bulk of “fuel” for further star formation, which may contribute to the “quenching” of star formation. In fact, ULIRGs (i.e., gas-rich mergers) show dynamical evidence for spheroids in formation (e.g., Genzel et al. 2001), and the star formation history of poststarburst galaxy is consistent with the (U)LIRG origin (e.g., Poggianni & Wu 2000; Bekki et al. 2001; Kaviraj et al. 2007). Our detection of NaI D outflows in poststarburst galaxies strongly suggests that feedback mechanism affects the kinematics of cool interstellar gas well after the most intense phase of star formation. The fact that quite a few red-sequence galaxies host winds may not be surprising yet still a striking result. A vast majority of absorption-line studies of outflows in literature has been on vigorously star-forming systems. Using a plot similar to Fig. 1, Rupke et al. (2005a) showed that most outflows in infrared-selected galaxies were detected in the loci of low Mg I b and high Na I D absorption indices, i.e., young galaxies with high interstellar Na I D column (their Fig. 8). In contrast, the red-sequence galaxies with outflows in our sample can have a high Mg I b absorption index, reflecting the presence of intermediate to old stellar population, and are not clearly distinct from other red-sequence galaxies in an optical color magnitude diagram (Fig. 10). The apparent connection between outflows and high \( M_* \) poststarburst galaxies provides circumstantial evidence that outflows of cool gas contributes to more effective quenching of star formation.

How the progenitors of spheroidal galaxies in the local universe evolve into their current state remains a topic under vigorous investigation. While their stellar contents suggest that massive spheroids have been passively evolving and that their stellar mass changes little since \( z \sim 1 \) (e.g., Brinchmann & Ellis 2000; Bundy et al. 2005), the evolution of the luminosity function suggests that the number density of luminous red galaxies has increased by a factor of \( \sim 2 \) over the same period (e.g., Bell et al. 2004; Brown et al. 2007; Faber et al. 2007). Over the similar redshift range, star-forming galaxies have a relatively small spread in star formation rates at a fixed mass in the blue sequence (e.g., Noeske et al. 2007a), leading to a paucity of objects presumably in transition between the blue and red sequences. Furthermore, less massive spheroids have younger stellar contents (e.g., Treu et al. 2005) and the characteristic galaxy mass above which the star formation in galaxies quenched evolves over redshift in a downsizing fashion (Bundy et al. 2006), indicating that catastrophic transition events occur at a progressively lower mass toward lower redshift. The exact rate of transition is very difficult to estimate, yet indirect arguments favor rare and/or fast mechanism(s) (e.g., Blanton 2006). Gas-rich mergers perhaps contribute to some but not all of these blue-red transitions (Bundy et al. 2007). The qualitatively similar downsizing trend in star-forming galaxies and outflow hosts over \( z < 0.5 \) (§ 4.1), however, may imply that the mechanism responsible for downsizing of star formation may also accompany outflows. A rigorous conclusion must await the quantitative analysis of the sample which suffers less from small number statistics, selection effects, and incompleteness.

We must note that it is not clear that merger per se is a necessary precursor for outflows. The direct morphological evidence for interaction is not very strong in our outflows (a majority of outflows are of early-type; § 3.4), and we relied on an indirect argument that the formation of a spheroid must follow a merger-induced starburst, given their poststarburst signature. Since the timescale for mergers at high redshift to remain identifiable is shorter than a poststarburst phase, the scarcity of direct evidence may not immediately discount the importance of mergers. Yet the mounting evidence now show that a majority of \( z \sim 1 \) LIRGs are normal disk galaxies whose elevated star formation is not caused by interaction (e.g., Bell et al. 2005; Lotz et al. 2006). The gradual decline of star-forming efficiency in their disks may be responsible for much of the global trend seen in comoving SFR density. From our study alone, whether or not these disky LIRGs at high redshift host outflows is not clear; the nature of outflows in these objects could be different from merger-induced ones which our sample of outflows is likely to represent. It would be interesting to see how the presence of outflows at \( z \lesssim 1 \) contribute to the fate of \( z \sim 1 \) LIRGs down to \( z \sim 0 \), which may either stay but fade gradually within the blue sequence or go through rapid quenching of star formation to migrate to the red sequence. Given the strong evolution of galaxy properties in general (§ 4.1), our knowledge from the local study of LIRG-like outflows might not be relevant for high-\( z \) disky LIRGs. On the other hand, if the outflow strength correlates with some parameter such as the presence of nuclear activity or their degree of interaction in relation to their morphology among high-\( z \) LIRGs [as observed in local ULIRGs by Martin (2005)], deprivation of (cool) gas via superwind may be important in transforming star-forming disks into quiescent spheroids in catastrophic events at those redshifts. The detection rate of outflows in view of host galaxy morphology at \( z \lesssim 1 \) may provide some insight on the physical mechanism that maintains the bimodality in galaxy population since \( z \sim 1 \). A comparison of mass outflow rates in \( z \sim 1 \) LIRGs with different morphology would also make an interesting exercise to put some insight on the role of mass loading in the evolutionary histories of morphology and star formation. Fortunately, several useful UV resonance lines at different ionization states shift into visible window for \( z \sim 1 \) objects, so future surveys are in a better position to constrain mass loading from these lines (e.g., Murray et al. 2007). In any case, gas kinematics adds another useful and promising dimension to the study of galaxy evolution.
4.3. Star Formation versus AGN

It is generally assumed that superwinds are driven by thermalized energy output from supernovae. In principle, AGNs offer much larger repository of energy than supernovae, and the ubiquity of super-massive black holes in galactic spheroids inferred from the $M_{\text{bh}}-\sigma$ relation (e.g., Tremaine et al. 2002) and their co-evolution with the lookback time (e.g., Woo et al. 2006) suggests that the energy output from AGNs may play important roles in galaxy formation. While AGNs offer increasingly attractive solutions to the yet elusive mechanism for shutting off star formation in massive objects, where and how their energy output couples to the gas in and around galaxies remains to be identified. Recently, however, several observational studies have elucidated the connection between poststarburst and nuclear activity: host galaxies of quasars often show poststarburst signature in their continuum emission (e.g., Canalizo et al. 2006); the morphology of poststarburst galaxies often show a blue core, which produces a LINER spectrum (Yang et al. 2006); the optical emission-line ratios classify a majority of poststarburst galaxies into Seyfert/LINERs (Tremonti et al. 2005; Yan et al. 2006; Yan & DEEP2 Team 2006).

Low-ionization outflows are found to be faster in starburst galaxies with some indication of AGN (Martin 2005; Rupke et al. 2005b). In $z \sim 0.5$ poststarburst galaxy sample, Tremonti et al. (2007) find Mg II outflows of $\sim 1000$ km s$^{-1}$, much faster than the typical Na I D outflows in ULIRGs ($\sim 300$–400 km s$^{-1}$). These fast outflows in their galaxies at their post-quasar phase provides compelling evidence for quasar-driven outflows in poststarbursts. It is worth noting that, due to the difference in sample selection, our poststarburst outflows are likely to be observed in more typical poststarburst galaxies than those of Tremonti et al., i.e., the event which led to the suppression of star formation does not have to accompany quasar activity for us to classify them as poststarbursts. Although the exact values are physically meaningless (§ 2.5), our measurements imply Na I D outflow velocities of $\sim 100$ km s$^{-1}$ in general and do not favor one scenario over others as to the outflow driving mechanism. It is plausible that some of our poststarburst galaxies have gone through the kind of post-quasar phase that Tremonti et al. observed, but they do not all have to be.

Nonetheless, the fact that typical poststarburst galaxies show low-level nuclear activity seems convincing, given the recent studies of the line emission from red-sequence galaxies. In Fig. 17, we show the classification of Seyfert/LINER versus star formation using the $[\text{N}\,\text{II}]/H\alpha$ emission equivalent width ratio, such that log($[\text{N}\,\text{II}]/H\alpha) = -0.3$ divides the two classes. The spectral baseline restricts the $[\text{N}\,\text{II}]/H\alpha$ measurements to $z < 0.39$ objects. The use of $[\text{O}\,\text{III}]/H\beta$ allows us to extend the classification to $z > 0.39$ objects in which we see a majority of outflows, but the delineation of Seyfert/LINER and star formation becomes notoriously ambiguous when only that ratio is used. A comparison to Weiner et al. (2007) shows that all $z > 0.35$ outflows in our sample have H I I-region–like ratios in $[\text{O}\,\text{III}]/H\beta$, which is rather puzzling, given many of them are red galaxies where line emissions tend to originate from AGN/LINERs. Using $[\text{N}\,\text{II}]/H\alpha$, Fig. 17 shows a distribution of objects grossly consistent with Yan et al. (2006) i.e., line emission from the red sequence is dominated by Seyfert/LINER, while that from the blue cloud is mostly from star formation. Host galaxies of outflows...
flows appear to follow a similar distribution, yet the analysis suffers from small number statistics.

In Fig. 18, we have a slightly different view on the color distribution of galaxies in terms of the emission excitation. The advantage of adding the near-UV photometry to detect low-level star formation has been discussed in § 3.2. The small number of outflow host galaxies at $z < 0.39$ still limits our interpretation. Nevertheless, it is quite interesting that the transition from star formation to Seyfert/LINER, and then to no H$\alpha$ emission appears to happen along the stellar age sequence, and the abundance of Seyfert/LINERs is observed in the region occupied by the galaxies in transition, a significant fraction of which appears to host outflows (Fig. 13). Clearly, extending this analysis to higher redshift, where more outflows are expected, could help us understand the potential impact of winds in establishing the observed trend in terms of their driving mechanisms, although the temporal coexistence of relic outflows and current nuclear activity does not imply any causal connection. It is nonetheless intriguing that many of our outflows have been found in galaxies in transition, which lead us to important clues to understand what establish the evolving bimodality in galaxy population over much of the cosmic history. In red-sequence, poststarburst outflows we can now detect a signature of gaseous feedback that leaves its imprint on galaxies over a relatively long timescale ($\sim 1.5$ Gyr) and that has the power to observationally constrain different feedback models.

5. SUMMARY

We reported on a signal-to-noise–limited search for low-ionization outflows using the DEEP2 spectra of the $0.11 < z < 0.54$ objects in the AEGIS survey. Doppler shifts from the host galaxy redshifts were systematically searched for in the Na I D optical resonance absorption doublet. This is the very first time that a signature of galactic superwind is systematically looked for in the individual galaxy spectra from a modern, large spectroscopic redshift survey.

Our Na I D profile fitting method closely followed that of Rupke et al. (2005a), explicitly fitting the absorption line model parametrized by the wavelength and the optical depth at the line center, Doppler width, and covering fraction in a self consistent manner. The confidence intervals in the Na I D velocities were estimated through the Markov chain Monte Carlo sampling technique. This allowed us to evaluate the quality of Na I D velocity measurements visually in terms of probability distributions of model parameters. Although the spectral resolution and signal-to-noise limited us to studying the interstellar gas kinematics by fitting a single doublet component to each observed Na I D profile, LIRG-like outflows should have been detected at $\geq 6\sigma$ in absorption equivalent width down to the survey limiting signal-to-noise ($\sim 5$ pixel$^{-1}$) in the continuum around Na I D. That is, if a Na I D outflow of a comparable strength to the LIRGs detected by the Rupke et al. (2005b) survey is present in a spectrum, we are able to detect it in our survey.

The detection rate of LIRG-like outflow clearly shows an increasing trend with star-forming activity and infrared luminosity. However, by virtue of not selecting our sample on star formation, we also found a significant fraction of outflows in galaxies on the red sequence in the rest-frame $(U-B, M_B)$ color-magnitude diagram. Most of these red-sequence outflows are of early-type morphology and show the sign of recent star formation in their UV-optical colors; some show enhanced Balmer H$\beta$ absorption lines indicative of poststarburst as well as high dust extinction.

These findings suggested that galactic-scale outflows could have played an important role in quenching star formation in the host galaxies on their way to the red sequence. Given that outflows appear to well outline starbursts and present significant columns, the fate of relic winds may be studied in galaxies at their poststarburst phase and possibly later.

We also note that inflows are detected in some red, quiescent early-type galaxies. Although the definition of an inflow in this study is just symmetrically opposite to that of an outflow, the fact that we observe them in an entirely different yet distinct subsets of galaxies strongly indicates that our inflow detections are not spurious. However, with the difficulty in removing stellar absorption component at Na I D as well as the lack of immediate explanations for their driving mechanisms, the investigation of inflows was beyond the scope of this paper and will be explored in future studies.

Despite that the small number statistics as well as selection effects hindered our ability to rigorously characterize the nature of the host galaxies of outflows across a wide array of physical parameters accessible in the AEGIS survey, the initial analysis presented in this paper will help design future experiments on the impact of superwinds on galaxy evolution during the epoch when the star-forming properties of galaxies drastically change since $z \sim 1$. Observing outflows in galaxies at their transitional phase is a promising avenue for constraining the driving mechanisms of baryons cycling through the components that constitute the luminous part of the universe, as well as for directly quantifying how much gas joins in such process.

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The research presented in this paper made an extensive use of the Python programming language and the associated tools. PyRAF and PyFITS are products of the Space Telescope Science Institute, which is operated by AURA for NASA. The figures in this paper are all prepared by PyTioga$^{15}$, an open-source software for creating figures and plots using Python, PDF, and TeX.

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$^{15}$ PyTioga is available at http://pytioga.sourceforge.net/.
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developed in cooperation with the Centre National d’Études Spatiales of France and the Korean Ministry of Science and Technology. For the full acknowledgement of the AEGIS data set, please refer to Davis et al. (2007).

Last but not least, we wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

APPENDIX

MODELING THE Na ID ABSORPTION LINE

We closely follow the model presented by Rupke et al. (2002, 2005a); readers are strongly encouraged to refer to these papers for a thorough discussion. Only a single component of the Na ID doublet is fitted in each spectrum; that is, we assume that our fitting of one absorption doublet is sensitive to the bulk property of the multiple Na ID absorbing clouds integrated along the sightline. While this is certainly an oversimplification (see, e.g., Rupke et al. 2002, for how complex an absorption profile with several kinematic components can appear), the limited S/N does not allow more detailed analysis; for the cases in which observed Na ID absorption lines are well defined, the fitting results are reliable. The observed intensity profile I(λ) of an absorption line is fitted by a model profile parametrized in the optical depth space. That is, if the (velocity-independent) partial covering fraction is Cf, each Na ID doublet is modelled by

\[ I(\lambda) = 1 - C_f \left[ 1 - e^{-\tau_{\text{blue}}(\lambda) - \tau_{\text{red}}(\lambda)} \right], \]

where \( \tau_{\text{blue}}(\lambda) \) and \( \tau_{\text{red}}(\lambda) \) are the optical depths of blue and red components of the doublet as a function of wavelength \( \lambda \). (This expression is appropriate for a continuum-divided spectrum.) We assume that the velocity distribution of absorbing atoms within a cloud is Maxwellian, such that each absorption line is modelled as

\[ \tau(\lambda) = \tau_0 e^{-\left(\lambda - \lambda_0\right)^2 / (\lambda_0 b_D/c)^2}, \]

where \( \tau_0 \) is the optical depth at the line center \( \lambda_0 \), c the speed of light, and \( b_D \) is the Doppler parameter in units of speed. Since the ratio of oscillator strengths for blue and red sides of the Na ID doublet is two (Morton 1991), we may assume that the central optical depths are related via \( \tau_{\text{red}}/\tau_{\text{blue}} = 2 = \tau_{\text{blue}}/\tau_{\text{red}} \). Hence the intensity profile of each Na ID doublet component is

\[ I(\lambda) = 1 - C_f \left\{ 1 - \exp \left[ -2 \tau_0 e^{-\left(\lambda - \lambda_{\text{blue}}\right)^2 / (\lambda_{\text{blue}} b_D/c)^2} - \tau_0 e^{-\left(\lambda - \lambda_{\text{red}}\right)^2 / (\lambda_{\text{red}} b_D/c)^2} \right] \right\}, \]

where \( \lambda_{\text{blue}} = 5889.9512 \text{ Å} \) and \( \lambda_{\text{red}} = 5895.9243 \text{ Å} \) are the rest-frame central wavelengths (in air) of blue and red lines of Na ID doublet. As noted by Rupke et al. (2005a), the Maxwellian velocity distribution and velocity-independence of partial covering fraction are significant assumptions. In case there is an outflow, an observed Na ID absorption profile likely arises from several absorbing clouds entrained in a superwind (e.g., Fujita et al. 2008), so their bulk kinematics would not be described simply by a Maxwellian distribution. Furthermore, if for example a spherical virialized cloud cuts through a sightline, the covering fraction must depend on the velocity of the constituent particles in the cloud; thus the assumption of velocity independence for covering fraction is not entirely consistent in terms of physics. Nevertheless, our analysis does not benefit from relaxing these constraints, as the quality of data does not warrant that such detailed information can be extracted.

Before the above model is fitted, each spectrum around Na ID is divided by the pseudocontinuum, a straight line fitted to the variance-weighted spectra within the rest-frame regions of 5822–5842 Å and 5910–5930 Å; the ranges are chosen after visual inspection for the best continuum normalization centered around Na ID, while avoiding other prominent stellar absorption features as much as possible. In a very strong outflow, the nebular emission line He I \( \lambda 5876 \) can contaminate the bluest wing of a Doppler-shifted Na ID component. Visual inspection indicates that few spectra suffer from such a contamination, so no account is taken for the He I emission in our measurements.

We take \( \lambda_{\text{red}}, b_D, \tau_0, \) and \( C_f \) as model parameters to be estimated via the Metropolis-Hastings algorithm (Metropolis et al. 1953; Hastings 1970), which yields a more robust confidence interval on a model parameter than that derived from a covariance matrix, when the probability distribution of the model parameter cannot be described as Gaussian. The sampling method also improves over Rupke et al. in a sense that each Monte Carlo realization is not drawn from the “best” model which needs to be chosen a priori via least-square fitting, for example. The priors for the model parameters are assumed to have a uniform probability density over their upper and lower limits: 42 km s\(^{-1}\) < \( b_D \) < 700 km s\(^{-1}\), 0 < \( \tau_0 \) < 10\(^3\), 0 < \( C_f \) < 1, and \( \lambda_0 \) is constrained to be within \( \pm 700 \text{ km s}^{-1} \) of the systemic velocity. The \( \chi^2 \) probability distribution for the given degrees of freedom (i.e., the number of data points fitted minus the number of model parameters) is assumed for the likelihood function. Each sampling consists of \( 10^5 \) iterations.

The measurement pipeline is built on top of PyMC,\(^{16}\) which implements the Metropolis-Hasting algorithm as an MCMC sampler, and developed in Python. The distributions of model parameters are visually inspected with a graphical user interface (GUI) along various dimensions; see Fig. A1. The integrity of fitting to the data spectrum is checked at several interactively-picked points on the two-dimensional intensity map of the distributions of model parameters. The GUI-driven visual inspection guards against the fits latching on to low-S/N features and helps identify unphysical fit results. The distribution of \( \lambda_{\text{red}} \), marginalized over all the other parameters and convolved with the redshift uncertainty, needs to be roughly Gaussian and well bounded within \( \pm 700 \text{ km s}^{-1} \) to make it into the high-S/N Na ID velocity sample (§ 2.4). The software may be distributed electronically at a URL to be determined in future.

REFERENCES


\(^{16}\) The code and documentation are available at http://trichech.us/.
Fig. A.1.—A few output windows from the Na D measurement pipeline. In this figure, the distributions of model parameters are shown as the two-dimensional intensity colormaps. Any location on the graphical user interface (left) can be clicked on to extract the model spectrum overlayed on top of the data spectrum (right). The relatively high-(S/N)$_{red}$ spectrum yields well-behaving parameter distributions here. The figure also gives an example of typical model parameter distributions. On the left, the parameters plotted are $\tau$-$\lambda_{red}$ (top left), $b_D$-$\lambda_{red}$ (top right), $C_f$-$\lambda_{red}$ (bottom left), and $C_f$-$\tau_0$ (bottom right). If marginalized over the parameter against which they are plotted, the distributions of $\lambda_{red}$ and $b_D$ become roughly Gaussian, whereas those of $C_f$ and $\tau_0$ are not. It is apparent that $C_f$ is not well constrained for $C_f \gtrsim 0.15$, and $\tau_0$, while relatively well constrained, is highly correlated with $C_f$. See § 2.4 for detail.
