ON THE NATURE OF SODIUM EXCESS OBJECTS. I. DATA AND OBSERVED TRENDS

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ABSTRACT

Several studies have reported the presence of sodium excess objects having neutral atomic absorption lines at 5895 Å (Na D) and 8190 Å that are deeper than expected based on stellar population models that match the stellar continuum. The origin of these lines is therefore hotly debated. van Dokkum & Conroy proposed that low-mass stars ($\lesssim 0.3 M_\odot$) are more prevalent in massive early-type galaxies, which may lead to a strong Na i 8190 line strength. It is necessary to test this prediction, however, against other prominent optical line indices such as Na D, Mg b, and Fe 5270, which can be measured with a significantly higher signal-to-noise ratio than Na i 8190. We identified a new sample of roughly 1000 Na D excess objects (NEOs; $\sim$8% of galaxies in the sample) based on Na D line strength in the redshift range $0.00 \lesssim z \lesssim 0.08$ from the Sloan Digital Sky Survey (SDSS) DR7 through detailed analysis of galaxy spectra. We explore the properties of these new objects here. The novelty of this work is that the galaxies were carefully identified through direct visual inspection of SDSS images, and we systematically compared the properties of NEOs and those of a control sample of galaxies with normal Na D line strengths. We note that the majority of galaxies with high velocity dispersions ($\sigma_v > 250$ km s$^{-1}$) show Na D excesses. Most late-type NEOs have strong Hβ line strengths and significant emission lines, which are indicative of the presence of young stellar populations. This result implies that the presence of the interstellar medium and/or dust contributes to the increase in Na D line strengths observed for these galaxies, which is in good agreement with the earlier study of Chen et al. who used the Na D line index to study outflow activity in star-forming disk galaxies. In contrast, the majority of early-type NEOs are predominantly luminous and massive systems, which is in agreement with the findings of van Dokkum & Conroy. However, we find that models used to reproduce the Na i 8190 line strengths that adopt a bottom-heavy initial mass function are not able to reproduce the observed Na D line strengths. By comparing the observed Na D, Mg b, and Fe 5270 line strengths with those of the models, we identify a plausible range of parameters that reproduce the observed values. In these models, the majority of early-type NEOs are “α-enhanced” ([α/Fe] $\sim$ 0.3), “metal-rich” ([Z/H] $\sim$ 0.3), and, especially, “Na-enhanced” ([Na/Fe] $\sim$ 0.3). An enhanced Na abundance is a particularly compelling hypothesis for the increase in the strength of the Na D line index in our early-type NEOs that appear devoid of dust, both in their SDSS images and spectra.

Key words: catalogs – galaxies: abundances – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: spiral – galaxies: stellar content

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Deciphering galaxy spectra is important to understanding the formation and evolution of galaxies. Prominent absorption features of galaxy spectra are widely used to study galaxy properties, because they reflect the average surface gravities, effective temperatures, and metallicities of the stellar components.

The behavior of sodium spectral features in some galaxies has received much attention since some galaxies show enhanced Na D doublet strengths at 5890 and 5896 Å and Na i 8190 doublet strengths at 8183 and 8195 Å.

The Na D index is one of the strong absorption features of optical spectra, while Na i 8190 is one of the most prominent features in the near-IR (NIR) spectral range. Numerous studies have been performed over the last three decades to understand these lines. It is now generally recognized that these lines are affected by the choice of an initial mass function (IMF), because these lines are strong in stars with masses less than 0.3 $M_\odot$. However, it is important to keep in mind that the Na D feature is more sensitive to Na-enhancement ([Na/Fe]) than gravity, and that it can also be affected by the interstellar medium (ISM). Furthermore, both the Na D and Na i 8190 absorption features are sensitive to age and metallicity.

What, then, causes Na D excess objects (hereafter NEOs)? The mechanism leading to a Na D excess has been debated. One of the leading hypotheses is that the Na D excess is related to the ISM, even though it is unclear what the dominant process is: galactic-scale gaseous outflows (galactic winds) in actively star-forming galaxies or active galactic nucleus (AGN) activity. It is well known that galactic winds are ubiquitous in star-forming galaxies (Heckman et al. 1990); Chen et al. (2010) argued that Na D absorption arises from cool gas in the disk, which is entrained in the galactic wind. In contrast, Lehner et al. (2011) investigated the properties of Na D line strengths in a sample of radio galaxies and concluded that AGN activity plays an important role in powering the outflow/heat phase of the feedback cycle.

Another candidate to explain NEOs is metal abundance. The discovery of non-solar abundance patterns in early-type galaxies was first made by O’Connell (1976) and Peterson (1976). These authors found extreme enhancement of the Mg b and Na D features with respect to calcium and iron peaks, and concluded that this finding was a result of a higher metal abundance. Later, Carter et al. (1986) measured the Na i, Ca ii triplet, TiO, and FeH features of 14 early-type galaxies and confirmed that these features were associated with metal abundance (see also
Alloin & Bica 1989). Worthey (1998) also claimed that strong Na features were caused by an overabundance of [Na/Fe] (see also Worthey et al. 2011).

The latest compelling mechanistic theory is that of a variation in the IMF. The stellar IMF is usually considered a universal function, but the possibility of a non-universal IMF has been raised by several authors (see, e.g., Davé 2008; van Dokkum 2008; Trager et al. 2000; Graves et al. 2009; Treu et al. 2010; van Dokkum & Conroy 2010). One of the first observational attempts to constrain the low-mass portion of the IMF was made by Spinrad & Taylor (1971). They compared the observed line strengths of some IMF-sensitive lines such as Na i and TiO in the centers of M31, M32, and M81 with the population synthesis models and claimed that a substantial fractional contribution of the integrated light of galaxies came from dwarf stars. Cohen (1978) also measured the strengths of Na i 8190 and TiO in the centers of M31 and M32 and concluded that the IMF was equal to that of the Galactic disk. However, Faber & French (1980) argued for a bottom-heavy (dwarf-rich) IMF; despite the fact that their results were also based on the Na i 8190 line strengths of M31 and M32. Indeed, it is a challenge to estimate the number of low-mass stars from an integrated spectrum because low-mass stars are too faint to have a strong influence on the integrated spectrum.

The debate over IMF variation, however, was reopened by Saglia et al. (2002). These authors found an anti-correlation between the strength of the Ca ii triplet region at 8500 Å and the velocity dispersion of elliptical galaxies and concluded that bottom-heavy IMFs are favored (see also Cenarro et al. 2003). Recently, van Dokkum & Conroy (2010) reported observing the near-infrared Na i 8190 doublet in the spectra of massive early-type galaxies and claimed that this excess can be explained by a bottom-heavy IMF (see also van Dokkum & Conroy 2012). If correct, massive early-type galaxies should possess relatively more low-mass stars; this finding would affect the mass-to-light ratio (M/L) of galaxies. Cappellari et al. (2012) claimed that there was systematic variation in the IMF in early-type galaxies as a function of stellar M/L ratios based on detailed dynamical modeling of ATLAS3D early-type galaxies (see, e.g., Cappellari et al. 2011), but the expected maximum slope of the IMF is about 2.8 (x ~ -2.8), which is lower than that proposed by van Dokkum & Conroy (2010). Furthermore, there are many high velocity dispersion galaxies that prefer a Salpeter IMF (Salpeter 1955).

Three origins of the Na D excess have been hypothesized: (1) the ISM, (2) metallicity, and (3) a bottom-heavy stellar IMF. To determine which of the above is correct, we explore the properties of NEOs in the redshift range 0.00 ≤ z ≤ 0.08 and applying on absolute r-band magnitude cut-off of −20.5 to obtain a volume-limited sample. Furthermore, only galaxies with a signal-to-noise (S/N) ratio above 20 and a quality assessment value based on continuum fit (rN/sN; see Section 3 of OSSY) below 1.5 are included in our sample. These cuts guarantee high-quality spectroscopic data and model fits to the stellar continuum. The total number of galaxies in our sample is 20,571. Our selection criteria are summarized in Table 1.

### Table 1

| Criterion | Explanation |
|-----------|-------------|
| 0.00 ≤ z ≤ 0.08 | Limit redshift for morphological classification |
| M_r < −20.5 | The absolute r-band magnitude cut for a volume-limited sample |
| S/N > 20 | Guarantee the quality of spectroscopic data |
| rN/sN ≤ 1.5 | Guarantee the quality of the fit to the stellar continuum |

Note. Oh et al. 2011.

presented in Sections 3 and 4, respectively. Finally, we discuss the origin of NEOs in Section 5.

### 2. DATA CONSTRUCTION

#### 2.1. SDSS and OSSY Catalogs

SDSS has established the largest and most homogeneous database of both photometric (u, g, r, i, and z bands) and spectroscopic data for about one million galaxies. However, it is known that the SDSS pipeline spectroscopic data measurements still have a few crucial defects. The most serious problem is that the pipeline values for the absorption line strengths are contaminated by nebular emission. Oh et al. (2011, hereafter OSSY) recently released new and improved absorption and emission-line measurements for the SDSS galaxies using the Gas AND Absorption Line Fitting routine (GANDALF; Sarzi et al. 2006) and the penalized pixel-fitting code (pPXF; Cappellari & Emsellem 2004). Furthermore, OSSY provided information about the best-fit models for the SDSS spectra. We start the analysis based on this OSSY catalog.

We obtained photometric values from the Catalog Archive Server for DR7. We used Petrosian and model magnitudes to estimate galaxy luminosities and colors, respectively. We also dereddened the colors with respect to Galactic extinction using the dust maps provided by the SDSS pipeline (Schlegel et al. 1998) and applied a k-correction based on simple two-population (young plus old) modeling of the observed optical colors. The details of the k-correction are described more fully in Section 3 of Yi et al. (2011).

#### 2.2. Sample Selection

We begin by selecting all sample galaxies with spectra in the redshift range 0.00 ≤ z ≤ 0.08 and applying on absolute r-band magnitude cut-off of −20.5 to obtain a volume-limited sample. Furthermore, only galaxies with a signal-to-noise (S/N) ratio above 20 and a quality assessment value based on continuum fit (rN/sN; see Section 3 of OSSY) below 1.5 are included in our sample. These cuts guarantee high-quality spectroscopic data and model fits to the stellar continuum. The total number of galaxies in our sample is 20,571. Our selection criteria are summarized in Table 1.

#### 2.3. Measurement of Na D Excess

To find NEOs, we define a new index, fNaD, which quantifies the Na D excess as follows:

\[
f_{NaD} = \frac{NaD(\text{Observed}) - NaD(\text{Model})}{NaD(\text{Model})}, \quad (1)
\]

where Na D (Observed) is the observed Na D line strength and Na D (Model) is the expected model Na D line strength.
For example, a $f_{NaD}$ value equal to 1 indicates that the observed absorption strength of Na D is two times stronger than that expected for the best-fit model. Details of the continuum fitting and absorption line measurements are described in OSSY, so we only briefly summarize the process here. The OSSY team first separated the contributions of the stellar continuum and ionized-gas emission to the observed spectrum by matching them only for emission-free regions using a set of stellar templates. They then measured the emission-line strengths by fitting stellar templates and Gaussian emission-line templates to the data. During this process, they used both the stellar population synthesis models of Bruzual & Charlot (2003) and the MILES stellar templates (Sánchez-Blázquez et al. 2006) and calculated internal reddening due to dust (see Section 3.5 for details). Finally, they subtracted the emission-line spectrum from the observed one to obtain the clean absorption line spectrum, and then measured the absorption line indices from this cleaned spectrum following standard line-strength index definitions.

In Figure 1, we plot the distribution of $f_{NaD}$ for the total sample of 20,571 galaxies. Interestingly, the distribution is skewed with a tail toward higher values. We fit a Gaussian curve to the Na D excess index distribution and plot it with a red dot-dashed line to highlight the presence of NEOs. Moreover, the peak of the distribution (vertical solid line) does not correspond to zero. In other words, more galaxies tend to have positive $f_{NaD}$ values than negative $f_{NaD}$ values.

We adopt a conservative limit of $f_{NaD} = 0.5$ to select galaxies showing a Na D excess. This demarcation for identifying NEOs ($f_{NaD} \geq 0.5$) is indicated by the vertical dashed line in Figure 1. The overall fraction of NEOs meeting our criterion is roughly 7.8% (1603/20,571). Interestingly, Na D deficient objects (NDOs) also exist. If we adopt a limit of $f_{NaD} = -0.5$ (vertical dotted line) to select NDOs ($f_{NaD} \leq -0.5$), the overall fraction of NDOs is about 0.6% (120/20,571). We note that most NDOs are strong emission-line galaxies. Bica & Alloin (1986) indeed reported that a few late-type galaxies show a Na D emission line. This result implies that the Na D absorption feature can be affected by the Na D emission line and that the continuum fits may be influenced by emission lines.

An important objective of this paper is a systematic comparison of the properties of NEOs and those of a control sample of galaxies that do not show a Na D excess. We create a control sample of $\sim$1600 galaxies in the Na D excess range $0.0 \leq f_{NaD} \leq 0.1$, based on the peak value of $f_{NaD}$ of about 0.1 (see Figure 1). The classification scheme is summarized below:

\begin{equation}
\begin{align*}
    f_{NaD} &\geq 0.5 & \text{Na D excess objects (NEOs)} \\
    0.0 &\leq f_{NaD} &\leq 0.1 & \text{Control sample} \\
    f_{NaD} &\leq -0.5 & \text{Na D deficient objects (NDOs)}. \\
\end{align*}
\end{equation}

Observed stacked spectra of sample galaxies (black solid lines) with their stacked best fits (red dot-dashed lines), normalized at 5800 Å, are shown in Figure 2. We constructed the stacked galaxy spectra by selecting $\sim$300 early-type looking galaxies in the $f_{NaD}$ range $0.0 \leq f_{NaD} \leq 0.1$ (for the control sample) and $f_{NaD} \geq 0.5$ (for the NEOs). We also estimated the 1σ scatter (gray lines). The overall observed spectra match the models well. However, there is a marked discrepancy in the fit in the specific index region for sodium near 5900 Å. The vast majority of the spectra are well matched (left), but some galaxies (NEOs, $\sim$ 7.8%) show a much stronger observed line index than expected based on the best-fit model (right). We note that the expected model Na D line strengths of the control sample and the NEOs are almost the same.

2.4. Visual Classification

As the final step, we perform visual classification of the sample. Images used for morphological classification are those provided by the SDSS DR7 release. The sample galaxies showing Na D excess are carefully assigned to four main classes: (1) ordinary early-type galaxies (oETGs), (2) peculiar early-type galaxies (pETGs), (3) ordinary late-type galaxies (oLTGs) and (4) peculiar late-type galaxies (pLTGs). Note that galaxies that exhibit any asymmetric features (i.e., shells and tails), dust patches, or dust lanes (especially for early-type galaxies) are classified as peculiar galaxies, that is, categories (2) or (4). The aim of our classification scheme, therefore, is to construct robust ordinary samples (categories (1) and (3)). There are, however, little differences among late-type galaxies. We use only two categories for the control sample: early-type galaxies and late-type galaxies.

Additionally, we keep the galaxy in a sample if we can precisely classify it morphologically. When we are unsure of the classification, the galaxy is classified as an unknown galaxy. This process yields a final sample of 206 reliably classified oETGs, 347 pETGs, 56 oLTGs, 354 pLTGs, 694 early-type control samples, and 342 late-type control samples. Details are listed in Table 2 and sample galaxies are shown in Figures 3–5. Figure 6 shows a plot of the redshift distributions of NEOs and control sample galaxies. Note that we initially constructed a volume-limited sample, but using an S/N cut and visual classification led to the exclusion of a fair fraction of more distant galaxies from our sample. It is also interesting to note that only 15% of galaxies that show extreme Na D excess ($f_{NaD} \geq 1.0$) are classified as early-type galaxies.

3. PROPERTIES OF EARLY-TYPE Na D EXCESS OBJECTS

3.1. Color–Magnitude Relation

The color–magnitude relation (CMR) is widely used to study the star formation history of galaxies. Galaxies are populated
Figure 2. Sample SDSS stacked spectra of our control sample galaxies and Na D excess objects. The observed spectra, including the 1σ scatter, are shown by the black solid lines, together with their best fits (red dot-dashed lines). The bottom figures show the spectra in the regions of the Na D feature. The spectra were normalized at 5800 Å.

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

Figure 3. Sample SDSS color-composite images of our ordinary (oETGs; top) and peculiar (pETGs; bottom) early-type Na D excess objects. Each image covers 100′ × 100′.

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

in three main regions of the color–magnitude diagram: the red sequence, the blue cloud, and the green valley in between. It is known that the optical CMR of early-type galaxies shows a small scatter around the mean relation. In other words, almost all of the early-type galaxies are on the red sequence.

Figure 7 shows the $u-r$ CMR. The $u-r$ CMR is a particularly good tool for tracking the presence of young stellar
populations. Gray contours, red filled circles, and red open circles indicate the early-type control sample, ordinary early-type NEOs, and peculiar early-type NEOs, respectively. A cursory glance at this diagram shows that most ordinary early-type NEOs (oETGs; filled circles) reside in the well-defined red sequence, while peculiar early-type NEOs (pETGs; open circles) show a wide color baseline. This result is because our morphological classification scheme for peculiar galaxies allows for a wide variety of galaxies, ranging from dusty red galaxies to star-forming blue galaxies possessing shells, tidal features, and signatures of recent star formation. The $M_r$ and $u - r$ color distributions of the ordinary (red hashed) and peculiar (red solid) early-type NEOs compared to those of their control-sample counterparts (gray filled) are shown in Figure 7. Ordinary early-type NEOs are more luminous and optically redder than the control sample. Meanwhile, the majority of peculiar early-type NEOs are also slightly more luminous and redder than the control sample, but vary in luminosity and color.

### 3.2. Velocity Dispersion and Stellar Mass

Stellar velocity dispersion is one of the important physical parameters of galaxies and can be used to estimate galaxy mass by applying the virial theorem or a related method. Because SDSS fibers have a fixed diameter, we apply an aperture correction to the observed velocity dispersion using...
Figure 6. Top: redshift distribution of our visually classified ordinary (red hashed) and peculiar (red solid) early-type NEOs. The gray filled histogram represents the early-type control sample. Bottom: redshift distribution of our visually classified ordinary (blue hashed) and peculiar (blue solid) late-type NEOs. The gray filled histogram represents the late-type control sample. (A color version of this figure is available in the online journal.)

the following formula from Cappellari et al. (2006):

$$\sigma_e = \left( \frac{R_\text{fiber}}{R_e} \right) 0.066 \pm 0.035 \sigma_\text{fiber},$$  

(3)

where $R_\text{fiber}$ is the aperture radius of the SDSS fiber (1'5) and $R_e$ is the effective radius.

The stellar mass of each galaxy is also derived from its color and luminosity using the following formula from Bell et al. (2003):

$$\log \left( \frac{M_*}{M_\odot} \right) = -0.306 + 1.097(g - r) - 0.4(M_r, - M_{r, \odot}).$$

(4)

Figure 8 shows the stellar mass of our early-type sample as a function of velocity dispersion. Both ordinary (red filled circles) and peculiar (red open circles) early-type NEOs generally tend to have higher velocity dispersions and correspondingly higher masses than the majority of the control sample (gray contours). We also plot the distributions of velocity dispersion and stellar mass for ordinary (red hashed) and peculiar (red solid) early-type NEOs. The histograms for the control sample (gray filled) are also provided for comparison. We again find that ordinary early-type NEOs have significantly higher velocity dispersions and are relatively more massive systems than the average early-type control sample. Furthermore, we checked the velocity dispersions of all sample galaxies in the Na D excess range $0.0 \leq f_{NaD} \leq 0.1$ and found that only 0.5% (17/3461) of galaxies without a significant Na D excess have velocity dispersions greater than 250 km s$^{-1}$. This result implies that the majority of high velocity dispersion galaxies show a Na D excess. Our results are consistent with those of Spiniello et al. (2012) and Ferreras et al. (2013), who found a correlation between Na 8190 line strength and velocity dispersion. Meanwhile, peculiar early-type NEOs have a wide range of velocity dispersions.

3.3. Emission Line Diagnostics: Star Formation and AGN Activity

The ratios of emission lines can be used to distinguish various classes of emission line galaxies and ionization mechanisms. One of the most frequently used methods is the BPT diagram, proposed by Baldwin et al. (1981), on the basis of [O III] $\lambda 5007$/$H\beta$ and [N II] $\lambda 6583$/H$\alpha$ $\lambda 6563$ ratios. This method allows the classification of galaxies into star-formation-dominant and AGN-dominant galaxies.

BPT diagrams are shown in Figure 9 for the early-type control sample (left, black filled circles), ordinary early-type NEOs (middle, red filled circles), and peculiar early-type NEOs (right, red open circles). We note that galaxies in which all four emission lines are detected with an amplitude-over-noise
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Table 3
Results of Spectral Line Classification for Early-type Galaxies

| Classification  | Early-type Control Sample | Early-type NEOs | oETGs\(^a\) | pETGs\(^b\) |
|-----------------|---------------------------|----------------|-------------|-------------|
| Quiescent       | 88.8\% (616)              | 79.4\% (439)   | 90.8\% (187)| 72.6\% (252)|
| Strong emission | 11.2\% (78)               | 20.6\% (114)   | 9.2\% (19) | 27.4\% (95) |
| Star-forming    | 1.0\% (7)                 | 4.0\% (22)     | 0.0\% (0)  | 6.3\% (22)  |
| Composite       | 2.0\% (14)                | 5.8\% (32)     | 1.0\% (2) | 8.7\% (30)  |
| Seyfert         | 2.2\% (15)                | 1.4\% (8)      | 0.0\% (0)  | 2.3\% (8)   |
| LINER           | 6.0\% (42)                | 9.4\% (52)     | 8.2\% (17) | 10.1\% (35) |

Notes.
\(^a\) Ordinary early-type Na D excess objects.
\(^b\) Peculiar early-type Na D excess objects.

Figure 8. Top: distribution of velocity dispersions for our early-type sample. Early-type control sample, ordinary early-type NEOs, and peculiar early-type NEOs are represented as gray filled, red hashed, and red solid histograms, respectively. Bottom left: stellar mass of our early-type NEOs as a function of velocity dispersion. The ordinary early-type NEOs are shown using red filled circles. The peculiar early-type NEOs are plotted as red open circles. The contours of the early-type control sample (gray shaded) and all sample galaxies (dotted) are shown for comparison. Bottom right: distribution of stellar masses for our early-type sample.

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

(A/N from GANDALF, which is similar to the S/N) greater than 3 are classified as either “star-forming,” “composite,” (i.e., hosting both star formation and AGN activity), “Seyfert,” or “LINER” using the demarcation lines of Kaufrmann et al. (2003; dashed curve), Kewley et al. (2001, 2006; solid curve), and Schawinski et al. (2007; straight line). Galaxies without a detection in all four lines are classified as “quiescent” galaxies. Details are provided in Table 3.

Early-type NEOs exhibit a two-fold higher fraction of strong emission lines (\(~11\%) than the early-type control sample. Moreover, the fraction of early-type NEOs classified as “star-forming” is four-fold that of the control counterpart. The reason why early-type NEOs show a higher fraction of strong emission lines is mainly because of peculiar early-type NEOs. Most ordinary early-type NEOs are virtually free of emission lines (\(~91\%). It is also worth noting that the overwhelming bulk of emission in ordinary early-type NEOs is “LINER” AGN, which implies that ordinary early-type NEOs do not host both active star formation and powerful AGNs.

3.4. Absorption Line Strengths

Spectral line strengths have been used to understand the physical processes governing the evolution of galaxies because they reflect the average surface gravities, effective temperatures, and metal abundances of galaxies.

We first checked whether the observed spectra matched the models in specific index regions for Mg\(b\), Fe 5270, and H\(\beta\) by comparing the observed and expected model absorption strengths. The bottom three panels of Figure 10 show the Mg\(b\) (left; \(fMg b\)), Fe 5270 (middle; \(fFe 5270\)), and H\(\beta\) (right; \(fH\beta\)) excess indices, which were calculated using the same procedure as in Equation (1), against the Na D excess index \(fNaD\). The contours of the early-type control sample (gray shaded) and all sample galaxies (dotted) are shown for comparison. The top panels of Figure 10 show the distributions of \(fMg b\), \(fFe 5270\), and \(fH\beta\), respectively.

The early-type control sample and the NEOs have very similar distributions of Fe 5270 and H\(\beta\) excess indices; these distributions are furthermore Gaussian in shape, unlike the Na D distribution (see Figure 1). However, there is mismatch in the Mg\(b\) excess index between the observed and expected model strengths, especially for ordinary early-type NEOs (red hashed histogram and red filled circles). This Mg\(b\) excess in ordinary early-type NEOs indicates that for these galaxies, a mechanism explaining both the Na D and Mg\(b\) excesses is required, while \(fMg b\) is much smaller than \(fNaD\). For reference, the median values of \(fNaD\), \(fMg b\), \(fFe 5270\), and \(fH\beta\) for our early-type control sample are 0.06 \(\pm\) 0.03, 0.07 \(\pm\) 0.08, \(-0.05 \pm 0.10\), and 0.0 \(\pm\) 0.10, respectively, whereas those for ordinary early-type NEOs are 0.58 \(\pm\) 0.13, 0.26 \(\pm\) 0.11, \(-0.06 \pm 0.08\), and \(-0.06 \pm 0.09\), respectively.

We now turn to the line strength itself. Strong Balmer absorption lines (e.g., H\(\beta\)) betray the presence of young stars, while a combination of Mg\(b\) and Fe 5270 yields information about the mean metallicity of the population. In Figure 11, we show a comparison of \(fNaD\) and the line strength indices of Na D (left), Mg\(b\) (middle), and Fe 5270 (right). The Na D excess index \(fNaD\) correlates strongly with the Na D line strength. This result implies that NEOs are simply galaxies with strong Na D.
lines. This finding may occur because the best-fit models for early-type NEOs generally expect Na D line strengths of around 3.0 to 3.5 Å. Therefore, these galaxies have stronger Na D line strengths and higher Na D excesses. In contrast, the Mg b and Fe 5270 line strengths do not show significant correlations with fNaD due to contamination by peculiar early-type NEOs. Peculiar early-type NEOs show a wide range of Mg b and Fe 5270 values and often have much lower values than those of the early-type control sample. We note that some peculiar early-type NEOs with fNaD $\geq$ 1 have significantly weaker Mg b and
Fe 5270 line strengths than the early-type control sample. These features are similar to late-type NEOs, as discussed in Section 4 below.

In the top panels of Figure 11, histograms of the Na D, Mg b, and Fe 5270 line strengths are shown. Peculiar early-type NEOs have skewed distributions with a tail toward lower values for Mg b and Fe 5270. Their Mg b and Fe 5270 strengths are similar to those of late-type galaxies. If some peculiar early-type galaxies have recently formed stars that are centrally concentrated, these objects would show similar line strength distributions to late-type galaxies because the SDSS fibers encompass only the central regions.

Line strength index diagrams comparing Na D, Mg b, Fe 5270, and Hβ indices for the early-type control sample (gray shaded contours), ordinary early-type NEOs (red filled circles), and peculiar early-type NEOs (red open circles) based on the stellar population models of Thomas et al. (2003, hereafter TMB) are shown in Figure 12. Contours of all sample galaxies are also shown as dotted lines for comparison. For the Fe 5270–Mg b and Hβ–Mg b plots ((a) and (b), Figure 12), our sample galaxies follow the models reasonably well. The majority of (ordinary) early-type NEOs are old, consistent with an isochrone of 12 Gyr, metal-rich above the solar value, and over abundant in α-elements, which are the general characteristics of massive early-type galaxies (Rich 1988; Gorgas et al. 1990; Worthey et al. 1992; Trager et al. 2000; Thomas et al. 2005). However, some peculiar early-type galaxies have stronger Hβ line strengths than the early-type control sample, which is evidence of recent star formation (see, e.g., Yi et al. 2005; Kaviraj et al. 2007; Jeong et al. 2007, 2009; Suh et al. 2010; Crockett et al. 2011).

In the Na D−index plots ((c)–(e), Figure 12), the sample galaxies deviate significantly from the model grids. They show an enhancement of Na D with respect to Mg b, Fe 5270, and Hβ. This behavior indicates that the Na D line strengths of some galaxies, especially those with higher Na D strengths (Na D ≥ 4.0 Å), are difficult to replicate using stellar population models. This result brings stellar population models into question, consistent with previous suggestions (e.g., IMF variation and/or overabundance of [Na/Fe]), or indicates that the Na D excess may be caused by non-stellar components (e.g., the ISM and/or dust).

### 3.5. Impact of Interstellar Extinction

It is well known that the Na D index is influenced by the ISM; dust lanes provide additional absorption in this line. Some studies have reported that dust extinction correlates with Na D line strength (see, e.g., Bica & Alloin 1986; Chen et al. 2010; Poznanski et al. 2012). We therefore consider the impact of interstellar extinction on the Na D line index to check whether the observed Na D line strength of early-type NEOs can be explained by the ISM and/or dust.

The OSSY catalog provides two distinct $E(B−V)$ reddening measurements: (1) $E(B−V)_{\text{diffuse}}$, corresponding to a diffuse “screen” dust component that affects the entire spectrum and (2) $E(B−V)_{\text{nebular}}$, associated with a “nebular” component that impacts only the ionized-gas emission, which is known to be generally related to dust features (Sarzi et al. 2006). $E(B−V)_{\text{diffuse}}$ values can be reasonably estimated if the (good-quality) continuum spectra match well with those generated by stellar population models, as is the case for our sample galaxies, whereas $E(B−V)_{\text{nebular}}$ values can be constrained only in the
Figure 12. Index measurements of our early-type control sample (gray shaded contours), ordinary early-type NEOs (red filled circles), and peculiar early-type NEOs (red open circles) compared to the stellar population models of TMB. For comparison, the contours of all sample galaxies are shown as dotted lines. (A color version of this figure is available in the online journal.)

Figure 13. A comparison of $f_{NaD}$ and the dust extinction values of $E(B - V)_{diffuse}$ for our sample galaxies. The early-type control sample (gray filled) and our ordinary early-type NEOs (red hashed) have nearly identical distributions with very little dust extinction from a diffuse screen dust component. In fact, the uncertainties of our $E(B - V)_{diffuse}$ measurements are generally so small (less than 0.01 for spectra with an $S/N > 20$, our minimum data quality threshold; see Section 2.2 and Table 1) that our $E(B - V)_{diffuse}$ measurements are consistent with little or no diffuse dust in our ordinary early-type NEOs, which suggests that their Na D excess may be related to specific aspects of their stellar populations (e.g., different abundance patterns). In contrast, roughly 50% of peculiar early-type NEOs have significant $E(B - V)_{diffuse}$ values greater than 0.1. This result implies that our peculiar early-type NEOs are generally dustier systems than ordinary early-type NEOs and the early-type control sample. This finding is expected because we classified dust lane early-type NEOs as peculiar galaxies.

A comparison of $f_{NaD}$ and $E(B - V)_{nebular}$ values for our early-type NEOs and early-type control sample galaxies is shown in the right panels of Figure 13. The $E(B - V)_{nebular}$ values, especially those of the early-type control sample and the peculiar early-type NEOs, have skewed distributions with tails toward higher values. The extent of such tails most likely reflects the different incidence of ionized-gas emission in our early-type subsamples (see Table 3), as expected given the connection between dust features and emission-line regions (Sarzi et al. 2006), whereas the overall similarity of the distributions indicates that nebular dust is not related to the Na D excess.

4. PROPERTIES OF LATE-TYPE Na D EXCESS OBJECTS

4.1. Color–Magnitude Relation

It is now common practice to divide galaxy populations on a color–magnitude diagram. Late-type galaxies typically have bluer colors than early-type galaxies and seem to reside in the blue cloud or the green valley.

In Figure 14, we present the $u - r$ CMR (bottom left) with $M_r$ (top) and $u - r$ (bottom right) histograms of our late-type control sample (gray shaded contours and gray filled histogram), ordinary late-type NEOs (blue filled circles and hashed histogram, oLTGs), and peculiar late-type NEOs (blue open circles and solid histogram, pLTGs). A cursory inspection of the plot shows that our late-type NEOs have similar overall ranges of absolute $r$-band magnitudes and slightly bluer $u - r$ optical color distributions than the late-type control sample, in contrast to early-type NEOs, which are more luminous and optically redder than the early-type control sample. Our late-type NEOs also have a narrower range of $M_r$, but a wider range of colors, than our early-type NEOs. We note that the difference in peak position of ordinary late-type NEOs may be due to limited number statistics. It is also worth noting that our late-type sample contains a number of red spiral galaxies in the green valley and even in the red sequence.

4.2. Velocity Dispersion and Stellar Mass

The effective velocity dispersion and stellar mass of late-type galaxies are also derived using Equations (3) and (4), respectively. It is important, however, to recognize that these

presence of nebular emission. Moreover, $E(B - V)_{nebular}$ values depend on our assumption of an intrinsic Balmer decrement (for more details, see OSSY).

In the left panels of Figure 13, we show a comparison of $f_{NaD}$ and the dust extinction values of $E(B - V)_{diffuse}$ for our sample galaxies. The early-type control sample (gray filled) and our ordinary early-type NEOs (red hashed) have nearly identical distributions with very little dust extinction from a diffuse screen dust component. In fact, the uncertainties of our $E(B - V)_{diffuse}$ measurements are generally so small (less than 0.01 for spectra with an $S/N > 20$, our minimum data quality threshold; see Section 2.2 and Table 1) that our $E(B - V)_{diffuse}$ measurements are consistent with little or no diffuse dust in our ordinary early-type NEOs, which suggests that their Na D excess may be related to specific aspects of their stellar populations (e.g., different abundance patterns). In contrast, roughly 50% of peculiar early-type NEOs have significant $E(B - V)_{diffuse}$ values greater than 0.1. This result implies that our peculiar early-type NEOs are generally dustier systems than ordinary early-type NEOs and the early-type control sample. This finding is expected because we classified dust lane early-type NEOs as peculiar galaxies.

A comparison of $f_{NaD}$ and $E(B - V)_{nebular}$ values for our early-type NEOs and early-type control sample galaxies is shown in the right panels of Figure 13. The $E(B - V)_{nebular}$ values, especially those of the early-type control sample and the peculiar early-type NEOs, have skewed distributions with tails toward higher values. The extent of such tails most likely reflects the different incidence of ionized-gas emission in our early-type subsamples (see Table 3), as expected given the connection between dust features and emission-line regions (Sarzi et al. 2006), whereas the overall similarity of the distributions indicates that nebular dust is not related to the Na D excess.

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4.2. Velocity Dispersion and Stellar Mass

The effective velocity dispersion and stellar mass of late-type galaxies are also derived using Equations (3) and (4), respectively. It is important, however, to recognize that these
equations were derived mainly for early-type galaxies, which may lead to measurement errors when applying them to late-type galaxies.

Figure 15 shows the relationship between the velocity dispersion and stellar mass. The control sample (gray shaded contours) and late-type NEOs (blue filled and open circles) have very similar velocity dispersions and stellar mass distributions (or slightly lower velocity dispersions and smaller stellar masses), unlike the early-type case for which there was a correlation between Na D line strength and velocity dispersion. We also plot the distributions of velocity dispersion and stellar mass of the late-type control sample (gray filled), ordinary late-type NEOs (blue hashed), and peculiar late-type NEOs (blue solid). We again find that the velocity dispersion and stellar mass distributions of our late-type NEOs are virtually indistinguishable from those of their control counterparts.

4.3. Emission Line Diagnostics: Star Formation and AGN Activity

We begin our spectroscopic analysis by exploring the emission line diagnostic of our late-type galaxies using BPT diagrams (see Section 3.3 above).

BPT diagrams for our late-type galaxies are shown in Figure 16. Note again that we only plot galaxies where [N\text{II}], Hα, [O\text{III}], and Hβ lines are detected with A/N ≥ 3. Black filled circles (left) represent the late-type control sample, while ordinary and peculiar late-type NEOs are indicated by blue filled circles (middle) and blue open circles (right), respectively. To separate galaxies, we use the same demarcation lines as we used for early-type galaxies (see Section 3.3 and Figure 9). Table 4 summarizes the star-forming, composite, and AGN properties of our late-type galaxies.

Interestingly, almost 90% of late-type NEOs show significant emission lines, in contrast to early-type NEOs, which are virtually free of emission lines. Star forming galaxies, in particular, are more common in both ordinary and peculiar late-type NEOs. The fractions of late-type NEOs classified as star-forming and composite are larger by factors of four and two, respectively, than those of the late-type control sample, whereas the fractions classified as Seyfert or LINER are slightly lower. Therefore, it appears that Na D excess in late-type galaxies may be related to phenomena associated with star formation.

4.4. Absorption Line Strengths

We check again the excesses of Mg b, Fe 5270, and Hβ in late-type galaxies by comparing the line strengths between the observations and best-fit models. The bottom panels of Figure 17 show the Mg b (left; fMg b), Fe 5270 (middle; fFe 5270), and Hβ (right; fHβ) excess indices, which were calculated using the same procedure as in Equation (1). Blue filled and
Table 4
Results of Spectral Line Classification for Late-type Galaxies

| Classification         | Late-type Control Sample | Late-type NEOs | oLTGs<sup>a</sup> | pLTGs<sup>b</sup> |
|------------------------|--------------------------|----------------|--------------------|--------------------|
| Quiescent              | 57.6% (197)              | 13.4% (55)     | 14.3% (8)          | 13.3% (47)         |
| Strong emission        | 42.4% (145)              | 86.6% (355)    | 85.7% (48)         | 86.7% (307)        |
| Star-forming           | 12.0% (41)               | 41.0% (168)    | 39.3% (22)         | 41.2% (146)        |
| Composite              | 18.7% (64)               | 33.4% (137)    | 37.5% (21)         | 32.8% (116)        |
| Seyfert                | 5.6% (19)                | 4.2% (17)      | 1.8% (1)           | 4.5% (16)          |
| LINER                  | 6.1% (21)                | 8.0% (33)      | 7.1% (4)           | 8.2% (29)          |

Notes.

<sup>a</sup> Ordinary late-type Na D excess objects.

<sup>b</sup> Peculiar late-type Na D excess objects.

Figure 14. Same as Figure 7 but for the late-type control sample (gray filled histogram and shaded contours), ordinary late-type NEOs (blue hashed histogram and filled circles, oLTGs), and peculiar late-type NEOs (blue solid histogram and open circles, pLTGs).

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

Figure 15. Same as Figure 8 but for the late-type control sample (gray filled histogram and shaded contours), ordinary late-type NEOs (blue based histogram and filled circles; oLTGs), and peculiar late-type NEOs (blue solid histogram and open circles; pLTGs).

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

open circles represent ordinary and peculiar late-type NEOs, respectively. The dotted contours indicate the distribution of all sample galaxies, while the gray shaded contours indicate the distribution of late-type control sample galaxies. Note that most late-type NEOs have negative \( f_{\text{Mg}b} \) values, while early-type NEOs tend to have positive \( f_{\text{Mg}b} \) values (see Figure 10). This result is likely related to enhanced star formation in late-type NEOs, as discussed in Section 4.3. Late-type NEOs have \( f_{\text{Fe}5270} \) and \( f_{\text{H}\beta} \) distributions very similar with those of the late-type control sample.

In the top panels of Figure 17, we also plot the distributions of \( f_{\text{Mg}b} \), \( f_{\text{Fe}5270} \), and \( f_{\text{H}\beta} \). We confirm that the peak positions of the \( f_{\text{Mg}b} \) histograms for the late-type control sample (0.05) and late-type NEOs (−0.05) are slightly different.

In the cases of \( f_{\text{Fe}5270} \) and \( f_{\text{H}\beta} \), the distributions of late-type NEOs are virtually indistinguishable from those of their control counterparts (less than 0.03 difference on average), but late-type NEOs show wider deviations in \( f_{\text{Fe}5270} \) than the late-type control sample. For reference, the median values of \( f_{\text{Na}D} \), \( f_{\text{Mg}b} \), \( f_{\text{Fe}5270} \), and \( f_{\text{H}\beta} \) for our late-type control sample are 0.04 ± 0.03, 0.05 ± 0.08, −0.05 ± 0.09, and 0.00 ± 0.09, respectively, whereas those for ordinary late-type NEOs are 0.83 ± 0.52, −0.04 ± 0.15, −0.08 ± 0.16, and −0.03 ± 0.07, respectively.

Figure 18 shows the line strengths of Na D (left), Mg b (middle), and Fe 5270 (right) versus \( f_{\text{Na}D} \). We again see a correlation between \( f_{\text{Na}D} \) and Na D line strengths, as discussed in Section 3.4. In contrast, the Mg b and Fe 5270 line strengths...
do not show any significant correlations with $f_{\text{Na}D}$, but late-type NEOs (blue filled and open circles) tend to have weaker Mg $b$ and Fe 5270 line strengths than the late-type control sample (gray shaded contours) in contrast to the majority of early-type NEOs, which have stronger Mg $b$ and Fe 5270 line strengths.

In Figure 18, the Na D, Mg $b$, and Fe 5270 line strength distributions of late-type NEOs and those of their control-sample counterparts are shown; late-type NEOs have stronger Na D line strengths but weaker Mg $b$ and Fe 5270 line strengths than their control-sample counterparts.

In Figure 19, we show the absorption line measurements of our late-type galaxies compared to the stellar population models of TMB. The upper two panels show that our late-type galaxies are very well represented by a coeval (3 Gyr old) sequence of

Figure 16. Same as Figure 9 but for the late-type control sample (black filled circles; left), ordinary late-type NEOs (blue filled circles; middle), and peculiar late-type NEOs (blue open circles; right).

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

Figure 17. Same as Figure 10 but for the late-type control sample (gray filled histogram and shaded contours), ordinary late-type NEOs (blue hashed histogram and filled circles; oLTGs), and peculiar late-type NEOs (blue solid histogram and open circles; pLTGs).

(A color version of this figure is available in the online journal.)
models with various metallicities, while the lower three panels associated with the Na D line strength show that our data deviate from the model grids as in the case of early-type NEOs (see Figure 12). One notable difference is that most late-type NEOs tend to have weaker Mg $b$ and Fe 5270 line strengths with enhanced H$\beta$ strengths, which is further evidence of recent star formation, even though this process may not be directly connected to the Na D excess.

4.5. Impact of Interstellar Extinction

We consider again the impact of interstellar extinction by comparing the Na D excess index $f_{\text{NaD}}$ and the dust extinction values of $E(B - V)_{\text{diffuse}}$ and $E(B - V)_{\text{nebular}}$. We note that both ordinary and peculiar late-type NEOs stand out from the late-type control sample galaxies due to their much larger diffuse screen dust component values (left panel of Figure 20), whereas late-type control sample and late-type NEOs share very similar distributions of $E(B - V)_{\text{nebular}}$ (right panel of Figure 20). This result suggests not only that the ISM plays an important role in explaining the Na D excess found in late-type NEOs, but also that the ISM contribution to the Na D lines relates only to the diffuse dust component, which also reinforces our previous interpretation of Na D excess in ordinary (dust-free) early-type NEOs. We also further note that the lack of a connection between the nebular dust component and Na D excess is not completely unexpected if we consider that emission-line regions can be quite clumpy, so that only a small fraction of the stellar light encompassed by the SDSS spectra is covered.

According to some previous studies (see, e.g., Bica & Alloin 1986; Chen et al. 2010; Poznanski et al. 2012), the connection between diffuse screen dust extinction and Na D line strength can be evaluated quantitatively. Adopting the recent calibration of Poznanski et al. (2012) for the impact of interstellar absorption on Na D line strength (see their Equation (9)), the average $E(B - V)_{\text{diffuse}}$ value of $\sim 0.3$ mag (see Figure 20) observed in our late-type NEOs would be sufficient to explain the main peak shift of $\sim 1$ Å between the distributions of Na D line strengths for late-type NEOs and that corresponding to the late-type control sample (see Figure 18). This calibration also allows us to confirm that the impact of the ISM on Na D line strengths in our ordinary early-type NEOs is negligible, even when using a value of 0.01 Å as an upper limit for $E(B - V)_{\text{diffuse}}$, corresponding to typical uncertainties associated with this quantity (see Section 3.5).

5. DISCUSSION

A number of recent papers exploring Na features that are known to depend on surface gravity have indicated that there is an IMF variation among galaxies. To investigate the nature of NEOs, we selected Na D excess candidates in the redshift range $0.00 \leq z \leq 0.08$ from SDSS DR7 by adopting a new index, $f_{\text{NaD}}$. This index quantifies the Na D excess by comparing the observed spectrum with the best-fit model spectrum. Roughly 8% (1603/20,571, $f_{\text{NaD}} \geq 0.5$) of galaxies in the sample were classified as NEOs. These galaxies were then identified through direct visual inspection of SDSS images, resulting in a sample of 553 early-type and 410 late-type NEOs. An important goal of this paper was a systematic comparison of the properties of NEOs and those of a control sample based on homogeneous data sets. Note that only 0.5% of galaxies (17/3461) in the Na D excess range $0.0 \leq f_{\text{NaD}} \leq 0.1$ had high velocity dispersions greater than 250 km s$^{-1}$. This result implies that most high velocity dispersion galaxies are classified as NEOs. The results presented in Sections 3 and 4 indicate that the origin of the Na D excess may differ considerably depending on galaxy morphology.

The majority of early-type NEOs are optically redder, more luminous, more massive, and more likely to be high velocity dispersion systems than their early-type control sample.
counterparts. Furthermore, early-type NEOs are stronger in Mg $b$ and Fe 5270 than their control-sample counterparts, which have roughly solar abundance values (e.g., $[Z/H] \sim 0$ and $[\alpha/Fe] \sim 0$).

The mean observed Mg $b$ and Na D line strengths of the early-type control sample (black open diamond), ordinary early-type NEOs (red filled circle), and peculiar early-type NEOs (red open circle) with a specific stellar population model (black filled square) are shown in Figure 21. The errors correspond to standard deviations. A galaxy with an age of 12 Gyr and a solar metallicity (e.g., $[Z/H] = 0$, $[\alpha/Fe] = 0$ and [Na/Fe] = 0) with a Salpeter IMF (Salpeter 1955) based on the models of TMB (see also Lee et al. 2009; van Dokkum & Conroy 2012) will have Na D and Mg $b$ line strengths of 3.27 and 3.71 Å (black filled square), respectively. These model values are consistent with the observed values of early-type control samples (open diamond).

In contrast, the observed line strengths of early-type NEOs were notably different from the model values (see Figure 12). Given that the Na D index responds more strongly to [Na/Fe] than the IMF and that it is even influenced by the ISM, one might be tempted to disregard this mismatch. However, this mismatch is important because it provides information about the sodium abundance [Na/Fe]. To find stellar population models that reproduce the observed line strengths, we explored various factors that may increase the Na D, Mg $b$, and Fe 5270 line strengths based on the models of TMB (12 Gyr models), Lee et al. (2009, hereafter LWD; 12 Gyr models) and Conroy & van Dokkum (2012, hereafter CV; 13.5 Gyr models):

1. The $\alpha$-enhancement effect (green solid and dashed arrows in Figure 21): the Mg $b$ index, which is a well-known tracer of $\alpha$-elements, changes by 0.59 Å when $[\alpha/Fe]$ varies by +0.3 dex (TMB and LWD; green solid arrow), while Fe 5270 decreases by about 0.37 Å with increasing $[\alpha/Fe]$ (TMB and LWD). The effect of the $\alpha$-enhancement on Na D, however, is not clear. According to the models of TMB, the Na D feature increases slightly with $\alpha$-enhancement (see Figures 12(c) or 19(c)), whereas in the models of CV and LWD, the Na D line index weakens by about 0.55 Å on the $\alpha$-enhancement side ($[\alpha/Fe] = 0.3$). The green and black dashed curved arrows in Figure 21 represent these tendencies. This result means that $\alpha$-enhancement is not conducive to increasing Na D line strength, however, $\alpha$-enhancement is crucial to reproducing the observed Mg $b$ line strength and it is compatible with our general understanding of massive early-type galaxies (see, e.g., Rich 1988; Gorgas et al. 1990; Worthey et al. 1992; Trager et al. 2000; Thomas et al. 2005).

2. The metal effect (violet solid arrow in Figure 21): the Mg $b$ and Fe 5270 indices increase by about 0.73 and 0.52 Å, respectively, when $[Z/H]$ varies from 0.0 to 0.35 dex. An increase in $[Z/H]$ by 0.35 dex also causes an increase in the strength of Na D by about 1.10 Å (TMB).

3. The IMF effect (red solid arrow in Figure 21): the differences in Mg $b$ and Na D line strengths between the Salpeter and $x = -3$ bottom-heavy IMF are only 0.2 and 0.1 Å, respectively. This result implies that IMF variation has a limited impact on Mg $b$ and Na D (CV).

4. The Na-enhancement effect (blue solid arrow in Figure 21): the Na D line index is known to be particularly sensitive to [Na/Fe]. At [Na/Fe] = 0.3, Na D increases by about 1.1 Å (CV).
Given that massive early-type galaxies are known to have an overabundance of $\alpha$-elements and super-solar total metallicity, it is natural to assume that (ordinary) early-type NEOs have high $[\alpha/Fe]$ and $[Z/H]$ abundances. Furthermore, our early-type NEOs show strong $\text{Mg} b$ and $\text{Fe} 5270$ line strengths, as described above and in Section 3. Additionally, the observed $\text{Mg} b$ (4.82 Å) and $\text{Fe} 5270$ (2.98 Å) line strengths are consistent with the models of TMB (4.29 Å $\leq \text{Mg} b \leq$ 5.16 Å and 2.69 Å $\leq \text{Fe} 5270 \leq$ 3.15 Å when $[\alpha/Fe] = 0.3$ and $0.0 \leq [Z/H] \leq 0.35$) and Yi (2003) ($u-r = 2.74$ when $Z = 0.04$). However, the observed Na D line strength cannot be reproduced with these two assumptions, and the bottom-heavy IMF does not contribute substantially to increase the Na D strength. We therefore evaluated the hypothesis of enhanced Na abundance.

Most importantly, assuming that our early-type NEOs are "$\alpha$-enhanced", "metal-rich," and "Na-enhanced" without considering IMF variations, we found plausible parameters ($[\alpha/Fe] \sim 0.3$, $[Z/H] \sim 0.3$, and $[\text{Na}/\text{Fe}] \sim 0.3$) that reproduced the observed Mg $b$, Fe 5270, and Na D line strengths (see the black filled star and the red filled circle in Figure 21). A possible criticism is that the hypothesis of Na-enhancement to explain the Na excess is an ad hoc assumption. However, several
Figure 21. Response of Na D and Mg b line indices to changes in the abundance patterns ([α/Fe], [Z/H], and [Na/Fe]) and the IMF. The mean observed Na D and Mg b line strengths of the early-type control sample, ordinary early-type NEOs, and peculiar early-type NEOs are shown by the open diamond, the red filled circle, and the red open circle, respectively. The black filled star represents the vector sum excluding the IMF effect.

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

studies have pointed out the presence of Na-enhanced stars (see, e.g., Gratton et al. 2004; Fulbright et al. 2007). We stress that Na-enhancement also causes an increase in Na i 8190 strength and counteracts the effect of the bottom-heavy IMF.

Our analysis does not necessarily rule out the possibility of a bottom-heavy IMF. We simply report that Na D lines, though measured at a much higher S/N ratio than Na i 8190, are too strong in many massive early-type galaxies to be accounted for by the same bottom-heavy IMF models that van Dokkum & Conroy (2010) used to match the Na i 8190 lines. While Na-enhancement is discussed here, we have not fully explored its effects on other line indices (e.g., Mg b and Fe 5270). This analysis will be presented in a forthcoming paper based on new stellar population synthesis models. One more aspect to pay attention to is the NIR flux. Worthey et al. (2011) claimed that such bottom-heavy IMFs would yield redder NIR colors. In another forthcoming companion paper, we will also explore the multi-band (including NIR) photometric properties of NEOs.

The ISM and dust could also increase the Na D line strength. However, we classified the dust-lane galaxies as peculiar galaxies during the visual inspection stage (see Section 2.4). Notwithstanding that diffuse dust is essentially invisible in optical imaging, our ordinary early-type NEOs are at least free of clumpy dust and emission lines (see Figure 9 and Table 3). Furthermore, there was no correlation between the $E(B-V)_{\text{diffuse}}$ values from the OSSY catalog and $f\text{NaD}$, at least for ordinary early-type NEOs, and the $E(B-V)_{\text{diffuse}}$ values of ordinary early-type NEOs were nearly zero (see Figure 13). This result implies that the ISM and/or dust do not enhance the Na D line strength of ordinary early-type NEOs in a significant way. Nevertheless, a study of the presence and properties of the ISM in early-type NEOs is desirable because it is known that a significant fraction of early-type galaxies contain some cool ISM and dust (see, e.g., Jura et al. 1987; Knapp et al. 1989).

In contrast, the mechanism for Na D excess in late-type NEOs, including a small fraction of peculiar early-type NEOs that showed very similar trends to the late-type NEOs, appears to be different from that of the majority of early-type NEOs. In contrast to early-type NEOs, enhanced star formation was indicated both by strong H β absorption line strengths and by the higher fraction that were classified as star-forming based on BPT diagnostics. An intriguing property worth discussing here is that late-type NEOs generally have weak Mg b and Fe 5270 line strengths. In that sense, these galaxies could correspond to objects like NGC 3032 and 4150 observed in the course of the SAURON survey (see, e.g., de Zeeuw et al. 2002) that experienced recent star formation (Jeong et al. 2009). These characteristics may be caused by young stars (Crockett et al. 2011; Kaviraj et al. 2012). The fact that late-type NEOs have extra young stars is not directly related to Na D line strength, because this fact would reduce Na D line strength rather than enhance it. However, the presence of star formation and nuclear activity in these galaxies implies the availability of gas and dust, which can impact Na D line strength. Furthermore, we found that our late-type NEOs tended to have larger $E(B-V)_{\text{diffuse}}$ values than the late-type control sample (see Figure 20), in contrast to early-type NEOs.

We thus conclude that early-type (excluding a small fraction of peculiar early-type NEOs) and late-type NEOs have completely different mechanisms underlying their enhanced Na D strengths. The origin of Na D excess in early-type galaxies is not clear yet, but it is clear that early-type NEOs have Na-enhanced populations. The effects of Na-enhancement on individual line strengths will be elucidated in a companion paper. Meanwhile, Na D line strengths in late-type NEOs and a small fraction of peculiar early-type NEOs are highly contaminated by the ISM and/or dust. To facilitate follow-up observations of these exciting objects, we provide a catalog of all Na D excess objects presented in this paper in Table 5.

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