EFFECT OF INCLINATION OF GALAXIES ON PHOTOMETRIC REDSHIFT

CHING-WA YIP1, ALEX S. SZALAY1,2, SAMUEL CARLILES2, AND TAMÁS BUDAVÁRI1

1 Department of Physics and Astronomy, The Johns Hopkins University, 3701 San Martin Drive, Baltimore, MD 21218, USA; cwyip@pha.jhu.edu, szalay@jhu.edu, budavari@jhu.edu

2 Department of Computer Science, The Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA; carliles@pha.jhu.edu

ABSTRACT

The inclination of galaxies induces both reddening and extinction to their observed spectral energy distribution, which in turn impact the derived properties of the galaxies. Here we report a significant dependence of the error in photometric redshift (photo-z) on the inclination of disk galaxies from the Sloan Digital Sky Survey. The bias in the photo-z based on the template-fitting approach increases from −0.015 in face-on to 0.021 in edge-on galaxies. A Principal Component Analysis on the full sample of photometry reveals the inclination of the galaxies to be represented by the second mode. The corresponding eigenspectrum resembles an extinction curve. The isolation of the inclination effect in a low-order mode demonstrates the significant reddening induced on the observed colors, leading to the over-estimated photo-z in galaxies of high inclinations. We present approaches to correct the photo-z and the other properties of the disk galaxies against the inclination effect.

Key words: galaxies: fundamental parameters – methods: data analysis

Online-only material: color figures

1. MOTIVATION

The inclination of galaxies has been used as a tool to infer the opacity of disk galaxies (e.g., Holmberg 1958; Disney et al. 1989; Valentijn 1990; Huizinga & van Albada 1992; Davies et al. 1993; Giovanelli et al. 1994; Boselli & Gavazzi 1994; Davies & Burstein 1995). The effect of the inclination on disk galaxies is twofold: the reddening and the extinction on its spectral energy distribution, supported by many of the recent studies based on large samples of galaxies (e.g., Masters et al. 2003, 2010; Driver et al. 2007; Shao et al. 2007; Bailin & Harris 2008; Unterborn & Ryden 2008; Padilla & Strauss 2008; Maller et al. 2009; Yip et al. 2010; Conroy et al. 2010). If these effects are not corrected for, one would expect an impact on the derived properties of the galaxies. One such property is the photometric redshift (photo-z) of a galaxy, because it relies on the observed colors and magnitudes (e.g., Koo 1985; Connolly et al. 1995a) of the galaxy.

Many panoramic sky surveys will measure primarily broad-band photometry of galaxies. Considering how the distance to a galaxy has an influence from the inferred properties of the galaxy to the large-scale structures in the universe, the correct estimation of the photo-z of galaxies is of utmost importance. Studies in cosmology are also impacted by the accuracy in the redshift of galaxies of various inclinations. Notably, Marinoni & Buzzi (2010) have recently constrained dark energy content with statistics of the inclination of galaxies in pairs where the redshifts are known. We therefore explore and quantify in this work the dependence of the error in the photo-z on the inclination of disk galaxies. Among all of the Hubble morphological types, the geometry of disk galaxies deviates substantially from the spherical symmetry. One would expect a relatively large amplitude in any inclination-dependent effect.

We present the sample of disk galaxies in Section 2. We quantify the photo-z error as a function of the inclination of the galaxies in Section 3. We present approaches to correct the photo-z and the other properties of the disk galaxies against the inclination effect in Section 4.

2. SAMPLE

The galaxies in this study constitute a volume-limited sample from the Sloan Digital Sky Survey (SDSS; York et al. 2000) in which the redshift ranges from 0.065 to 0.075 and the r-band Petrosian absolute magnitude ranges from −19.5 to −22. To construct this sample we use the same selection criteria as described in Yip et al. (2010, hereafter Paper I), in which the authors derived the extinction curves of star-forming disk galaxies from the SDSS spectroscopy in the Data Release 5 (DR5; Adelman-McCarthy et al. 2007). In this work we consider instead the DR6 (Adelman-McCarthy et al. 2008), because of the improved photometric calibration and the larger number of galaxies. The other main characteristic of the sample is that, in the above ranges of redshift and absolute magnitude, the distribution of the inclination of the disk galaxies is uniform (see Figure 2(b) of Paper I). As such, the properties of the galaxies are not biased from one inclination to the next. There are 6285 galaxies in total in the analysis, a 36% increase from DR5.

We follow Paper I and use the r-band apparent minor to major axis ratio (b/a, or the derived parameter “expAB_r” in the SDSS) as a proxy for the inclination of the galaxies. The uncertainty in using b/a as an inclination measure is considered by simulating two-dimensional sky projections of the disk galaxies, where each galaxy is modeled as a triaxial spheroid at various known inclinations. With the premise that the disk galaxies are nearly circular (supported most recently by Ryden 2004 who obtained average face-on ellipticity of 0.16 for a sample of disk galaxies in the SDSS) and negligible disk scale height, not surprisingly we come to a similar conclusion as Shao et al. (2007) that the apparent axis ratio is a good measure for the inclination of disk galaxies. This conclusion is drawn based on the positive correlation of the simulated inclination and the apparent axis ratio. We decide to discuss the details of the simulation in a separate paper due to the limited space here.
We consider inclination ranges 0.0–0.2, 0.2–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.7, 0.7–0.8, 0.8–0.9, and 0.9–1.0 when calculating the photo-z statistics. To follow the convention in the SDSS all of the spectral energy distributions are expressed in vacuum wavelengths.

3. DEPENDENCE OF PHOTOMETRIC REDSHIFT ERROR ON INCLINATION OF DISK GALAXIES

3.1. Photo-z Error Versus Inclination

The photo-z error, \( z_{\text{photo}} - z_{\text{spec}} \), as a function of the inclination of the disk galaxies is shown in Figure 1. Three cases are considered: in Figure 1(a) the SDSS photo-z based on the template-fitting approach (Csabai et al. 2003, and references therein); in Figure 1(b) the SDSS photo-z by using the Artificial Neural Network approach (Oyaizu et al. 2008), in which the authors used an implementation similarly to that of Collister & Lahav (2004); and in Figure 1(c) the photo-z calculated in this work based on the Random Forest approach (Carli et al., 2010, details are deferred to Section 4.3). The “CC1” photo-z of Oyaizu et al. (2008) are used, because they were obtained by employing only four SDSS colors \( u-g, g-r, r-i \), and \( i-z \) in the training procedure, in this sense similar to Figure 1(c). While both the bias \( \langle z_{\text{photo}} - z_{\text{spec}} \rangle = -0.004 \pm 0.001, 0.003 \pm 0.001, 0.003 \pm 0.0003 \) and the root mean square (rms) \( \sqrt{ \langle (z_{\text{photo}} - z_{\text{spec}})^2 \rangle } = 0.032 \pm 0.002, 0.020 \pm 0.001, 0.018 \pm 0.0005 \) are, respectively, of the same order of magnitudes for all of the cases, the dependences on the inclination are noticeably different. In the template-fitting approach the bias in the photo-z increases from the face-on to edge-on galaxies, in such a way bias(edge-on)−bias(face-on) = 0.036. The photo-z bias also changes sign with inclination, showing that it is the ensemble bias \( (-0.004 \pm 0.001) \) being minimized instead of the bias for a particular group of galaxies. The statistics of the photo-z error in all of the inclination bins are given in Table 1. In contrast, the photo-z error does not show prominent dependence on the inclination of the disk galaxies in both of the machine learning approaches (Figures 1(b) and (c)). Because the inclination is not included explicitly in the training procedure in both of these approaches, this lack of inclination dependence is interpreted as the success of the methods in segregating the photometry of the disk galaxies by their inclination. The inclination of the galaxies therefore impacts their observed photometry, which in turn can

---

**Table 1**

| \( b/a \) | Number | Mean\(^a\) | Median | Sigma | Relative Bias\(^b\) |
|---------|--------|-----------|--------|-------|---------------------|
| 0.17    | 272    | 0.021     | 0.020  | 0.038 | 0.036               |
| 0.25    | 829    | 0.014     | 0.013  | 0.034 | 0.028               |
| 0.35    | 942    | 0.006     | 0.005  | 0.041 | 0.021               |
| 0.45    | 806    | -0.004    | -0.009 | 0.032 | 0.011               |
| 0.55    | 783    | -0.008    | -0.015 | 0.030 | 0.007               |
| 0.65    | 729    | -0.011    | -0.017 | 0.032 | 0.004               |
| 0.75    | 736    | -0.012    | -0.019 | 0.030 | 0.003               |
| 0.85    | 759    | -0.013    | -0.021 | 0.032 | 0.001               |
| 0.94    | 429    | -0.015    | -0.021 | 0.028 | 0.000               |

---

\(^a\) The mean \( \pm 1\sigma \) sample scatter of the apparent minor to major axis ratio in the sample of disk galaxies.

\(^b\) The ensemble bias is equal to \(-0.004 \pm 0.001\) or close to zero. Therefore, the mean photo-z error in each inclination bin is effectively the bias in the inclined galaxies relative to that in the full sample.

---

\(^3\) Here we are effectively considering galaxies with inclinations from 0.1 to 0.2 because there are only two galaxies with inclinations from 0.0 to 0.1. We however determine to set the inclination range of the first bin to be 0.0–0.2, so that all of the edge-on galaxies can be included.

\(^4\) The galaxies with photo-z bias \(< -0.05 \) in Figure 1(a) may be a result of larger uncertainty in the colors. The 1\sigma uncertainty in \( u-g \) for those with bias \(< -0.05 \) is 0.12 \pm 0.19, and that for bias \( > -0.05 \) is smaller by about half, 0.065 \pm 0.058.

\(^5\) In this work the biases are given to one significant figure and the rms’s to three decimal places, both \( \pm 1\sigma \) uncertainty.

---

Figure 1. Photo-z error as a function of the inclination of the disk galaxies. The top panels are scatter plots, with the error bar represents the mean \( \pm 1\sigma \) sample scatter of the binned data. The bottom panels show the corresponding number contours, smoothed over a 12 × 12 grid within the shown plotting ranges. The photo-z shown in panels (a) and (b) are taken from the SDSS DR6. The Random Forest photo-z are calculated in this work, shown in panel (c). (a) The photo-z based on the template-fitting approach. (b) The “CC1” photo-z based on the Artificial Neural Network approach. (c) The photo-z based on the Random Forest approach.

(A color version of this figure is available in the online journal.)
Figure 2. First (blue) and second (red) eigenspectra constructed from the photometry of our disk galaxy sample. The extinction curve from Paper I is plotted for comparison, as the black line. The second eigenspectrum resembles the extinction curve.

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

The Astrophysical Journal, 730:54 (7pp), 2011 March 20

Yip et al.

Figure 3. Comparison of the distribution of the eigencoefficients between the face-on (blue) and edge-on (red) galaxies, from the first ($a_1$) to the fifth ($a_5$, or the last) modes in a Principal Component Analysis (PCA). Among all of the PCA modes, the variance in the photometry of the disk galaxies due to their inclination is best described by the second mode.

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

be learned by a machine learning approach. We investigate how the inclination of galaxies impacts their observed photometry in the next section.

3.2. Variance in Photometry due to Inclination of Disk Galaxies

Next, we seek to understand why the photo-z error correlates with the inclination of the photometry of the disk galaxies. Our approach is to establish the variance in the galaxy sample and its relation to the parameter(s) of interest, or the inclination of the galaxies in the current context. The Principal Component Analysis (PCA), which is adopted here, was shown to be a powerful technique for this purpose (e.g., Madgwick et al. 2003; Yip et al. 2004). PCA identifies directions (or eigenvectors) in a multi-dimensional data space such that they represent the maximized sample variance. The lower the order of eigenvector, in this case the eigenspectrum (Connolly et al. 1995b), the more sample variance it describes. After relating the sample variance with the inclination, if possible, we can examine the involved eigenspectra to explain why in the edge-on galaxies the photo-z error is larger.

The first two eigenspectra calculated based on the photometry of the disk galaxies are shown in Figure 2. The first eigenspectrum resembles the mean spectrum of the galaxies. Perhaps more interestingly, the second eigenspectrum visually resembles the extinction curve obtained in Paper I, despite the fact that they are obtained by two completely different approaches (PCA versus composite spectra construction) and data sets (the photometry versus the spectroscopy of the galaxy sample). The discrepancy between the second eigenspectrum and the actual extinction curve is expected to be primarily due to variance in galaxy type within our disk galaxy sample.

To confirm that the second mode represents the inclination effect on the photometry, we examine the distribution of the eigencoefficients of various orders as a function of the inclination (Figure 3). The eigencoefficients of a galaxy are the expansion coefficients of its photometry onto the eigenspectra. A clear separation is seen in the distribution of the second eigencoefficients ($a_2$) between the face-on and edge-on galaxies. This separation is not seen, or is not as prominent, in the other orders of eigencoefficients. In other words, the second eigencoefficient is an indicator for the inclination of the disk galaxies.

Going back to Figure 2 to examine the eigenspectra, we see that the first eigenspectrum minus the second eigenspectrum results in a spectral energy distribution that is redder than the first eigenspectrum or the average galaxy spectrum. If the adopted theoretical model in the template-based photo-z does not take account of this reddening effect in the edge-on galaxies, the model would need to be shifted to a higher-than-true redshift in order to match the redder colors of the galaxies. This situation results in an over-estimation of the photo-z, or what is seen in Figure 1(a).

4. CORRECTIONS AGAINST THE INCLINATION EFFECT

We discuss approaches to correct various properties of the disk galaxies against the inclination effect. The parameters considered are the rest-frame magnitudes, the flux density in an arbitrary stellar population model for the galaxies, and the photo-z. There are obviously a wealth of other disk parameters that are expected to be subjected to the inclination effect. Some of those, including the surface brightness and the scale length, were discussed in detail in Graham & Worley (2008) and references therein.

4.1. On Rest-frame SDSS Magnitudes

We derive the following formulae for correcting rest-frame magnitudes of the whole disk galaxies in the SDSS $u, g, r, i, z$...
We used the magnitudes derived from convolving the spectra with filters in The Astrophysical Journal. The actual relative extinction versus galaxy at a given inclination. This functional form is taken to where in Equations (1)–(5), instead of the central 3σ (Stoughton et al. 2002). The 1σ uncertainties for the best-fit parameters are unbiased with inclination. On the other hand, the larger chisquares in the u and g bands suggest that the chosen relation may not be ideal. We therefore encourage the interpolation to the actual data listed in Table 2 when higher-accuracy corrections are required. We choose Equation (6) for the purpose of a direct comparison with literature (e.g., Unterborn & Ryden 2008; Yip et al. 2010), in which the powers of log10(b/a) have been considered. Only even integers are allowed in the power index because log10(b/a) is negative for all b/a values except unity. A power index of 4 is confirmed to provide a bad fit to our data, and a power index of 0 contradicts the data because it gives no b/a dependence. We plan to find other functional forms that may be unconventional but better describe the data. The rest-frame $M_{b/a}(b/a) - M_{b/a}$ versus $M_{b/a}(b/a) - M_{b/a}$ color–color diagram of our disk galaxies is shown in Figure 4, before and after the above inclination-dependent magnitude corrections. The average and the 1σ sample scatter of the colors of the edge-on galaxies are, before the corrections: 1.37 ± 0.25 (for color $M_{b/a}(b/a) - M_{b/a}(b/a)$), 0.57 ± 0.14 ($M_{b/a}(b/a) - M_{b/a}(b/a)$), and after the corrections: 1.14 ± 0.26 ($M_{b/a}(b/a) - M_{b/a}(b/a)$), 0.35 ± 0.14 ($M_{b/a}(b/a) - M_{b/a}(b/a)$). The before-and-after color offset is ≈0.2 for both the $M_{b/a}(b/a) - M_{b/a}(b/a)$ and $M_{b/a}(b/a) - M_{b/a}(b/a)$ colors. Obviously, the colors of the face-on galaxies remain unchanged: 1.11 ± 0.12 ($M_{b/a}(b/a) - M_{b/a}(b/a)$) and 0.39 ± 0.08 ($M_{b/a}(b/a) - M_{b/a}(b/a)$). For both colors, the offsets in the systematic locations between the edge-on galaxies and the face-on ones are greatly reduced after the corrections.

The second-order power dependence of the relative extinction of the whole galaxies on log10(b/a) agrees with that obtained by Unterborn & Ryden (2008). For the center of the disk galaxies (within 0.5 half-light radius), however, the extinction–inclination relation is steeper than a log10(b/a) dependence (Paper I). The difference likely reflects a higher extinction in the center relative to the edge of the galaxies, or an extinction radial gradient. We will investigate this finding in a separate paper.

### 4.2. On Flux Density of Stellar Population Models

The determination of many properties of galaxies, including the photo-$z$, involves fitting to the observational data a theoretical stellar population model. The model is defined by the related physical parameters, such as the stellar age and metallicity, at the correct amplitudes. In this kind of analysis, instead of correcting the observational data against the inclination effect as discussed previously, one can correct the theoretical model itself. The latter approach is at the expense of (or/and has the merit of) introducing the inclination of a galaxy as an extra parameter, which is to be determined simultaneously with the other properties during the minimization. Given a theoretical spectrum from a stellar population model, $f_{\nu}(b/a = 1)$, its

### Table 2

Relative Extinction as a Function of Inclination of Whole Disk Galaxies

| b/a | $M_{b/a} - M_{b/a}$ | $M_{b/a} - M_{b/a}$ | $M_{b/a} - M_{b/a}$ | $M_{b/a} - M_{b/a}$ | $M_{b/a} - M_{b/a}$ |
|-----|---------------------|---------------------|---------------------|---------------------|---------------------|
| 0.17 ± 0.0015 | 0.62 ± 0.03 | 0.31 ± 0.02 | 0.21 ± 0.03 | 0.10 ± 0.03 | 0.04 ± 0.03 |
| 0.25 ± 0.0010 | 0.46 ± 0.01 | 0.31 ± 0.02 | 0.16 ± 0.02 | 0.08 ± 0.02 | 0.04 ± 0.02 |
| 0.35 ± 0.0009 | 0.27 ± 0.02 | 0.16 ± 0.02 | 0.06 ± 0.02 | -0.00 ± 0.02 | -0.07 ± 0.02 |
| 0.45 ± 0.0010 | 0.17 ± 0.02 | 0.13 ± 0.02 | 0.07 ± 0.02 | 0.02 ± 0.02 | -0.03 ± 0.02 |
| 0.55 ± 0.0010 | 0.11 ± 0.02 | 0.11 ± 0.02 | 0.06 ± 0.02 | 0.05 ± 0.02 | 0.01 ± 0.03 |
| 0.65 ± 0.0011 | 0.03 ± 0.02 | 0.04 ± 0.02 | 0.01 ± 0.02 | -0.00 ± 0.02 | -0.02 ± 0.02 |
| 0.75 ± 0.0011 | 0.04 ± 0.02 | 0.05 ± 0.02 | 0.03 ± 0.02 | 0.02 ± 0.02 | 0.00 ± 0.03 |
| 0.94 ± 0.0012 | 0.00 ± 0.03 | 0.00 ± 0.03 | 0.00 ± 0.03 | 0.00 ± 0.03 | 0.00 ± 0.03 |

**Notes.** The SDSS model magnitudes are considered here.

1 The mean ±1 standard deviation of the mean (SDOM) of the apparent minor to major axis ratio in the sample of disk galaxies. The number of galaxies in each inclination bin is listed in Table 1.

2 The mean ±1 SDOM of the relative extinction.

### bands

$$M_{b/a}(b/a) = M_{b/a} - 1.14 \cdot \log_{10}^{2}\left(\frac{b/a}{a}\right), \quad (1)$$

$$M_{g}(b/a) = M_{g} - 0.76 \cdot \log_{10}^{2}\left(\frac{b/a}{a}\right), \quad (2)$$

$$M_{r}(b/a) = M_{r} - 0.39 \cdot \log_{10}^{2}\left(\frac{b/a}{a}\right), \quad (3)$$

$$M_{z}(b/a) = M_{z} - 0.17 \cdot \log_{10}^{2}\left(\frac{b/a}{a}\right), \quad (4)$$

$$M_{b}(b/a) = 0.00 \cdot \log_{10}^{2}\left(\frac{b/a}{a}\right). \quad (5)$$

The underlying calculation is similar to that in Paper I; as such we fit to the relative extinction versus $b/a$ data the following relation:

$$M(b/a) - M_{b} = \eta \cdot \log_{10}^{2}\left(\frac{b/a}{a}\right), \quad (6)$$

where $M(b/a)$ is the K-corrected absolute magnitude of a galaxy at a given inclination. This functional form is taken to be the same for all of the SDSS bands, and the proportional constant $\eta$ is fitted for each band. The left-hand side of Equation (6) is the relative extinction because $M(b/a) - M_{b} = A^{\text{intrinsic}}(b/a) - A^{\text{intrinsic}}(1)$ (see the Appendix for details). The actual relative extinction versus $b/a$ values are given in Table 2. The magnitudes of the whole galaxies are considered in Equations (1)–(5), instead of the central 3′-diameter areas of the galaxies that were considered in Paper I. In particular, the model magnitudes (“modelMag”) from the SDSS are used because they give unbiased colors of galaxies, a result of the flux being measured through equivalent apertures in all bands (Stoughton et al. 2002). The 1σ uncertainties for the best-fit $\eta$ are, respectively, 0.05, 0.03, 0.02, 0.01 in u, g, r, and i. The corresponding reduced chi-squares are 3.04, 2.79, 1.10, and 1.18. The points for the relative extinction $z(b/a) - z(1)$ versus inclination are scattered around zero and do not suggest any non-trivial functional form. We therefore do not attempt to fit the above relation in the z band and assign zero to the proportional constant (Equation (5)).

For the purpose of photo-z estimation, we will show in Section 4.3 that the color corrections derived from Equations (1)–(5) perform well, in the sense that the resultant photo-z are unbiased with inclination. On the other hand, the larger chisquares in the u and g bands suggest that the chosen relation may not be ideal. We therefore encourage the interpolation to the actual data listed in Table 2 when higher-accuracy corrections are required. We choose Equation (6) for the purpose of

6 We used the magnitudes derived from convolving the spectra with filters in the SDSS.
inclined flux densities can be calculated as follows:

\[ f_{\lambda}(b/a) = f_{\lambda}(1) \cdot s_{\lambda}(b/a), \]

(7)

where

\[ s_{\lambda}(b/a) = 10^{-0.4 \eta_{\lambda} \log_{10}(b/a)} \]

(8)
is derived from the extinction curve of the disk galaxies and its variation with inclination as given in Paper I. Here,

\[ \eta_{\lambda} = \sum_{j=0}^{3} a_{j} \tilde{\nu}^{j} \]

(9)

where \( b/a |_{\text{ref}} \) is a reference inclination. The wave number \( \tilde{\nu} \) is the inverse of wavelength, in the unit of inverse micron, \( \mu m^{-1} \). The coefficients \( a_{j} \) are listed in Table 4 of Paper I, where \( b/a |_{\text{ref}} = 0.17 \).

4.3. Photo-z from Random Forest Machine Learning

As presented above, the machine learning approaches give photo-z which do not show prominent bias with inclination. This result is not entirely surprising, if it is seen as the success of the methods in segregating the photometry of the disk galaxies by their inclination (see also Section 3). Here we consider the Random Forest approach, the power of which in estimating the photo-z is discussed in detail in Carliles et al. (2010). Basically, this method builds an ensemble of randomized regression trees and computes regression estimates as the average of the individual regression estimates over those trees. The trees are built by recursively dividing the training set into a hierarchy of clusters of similar galaxies. The procedure minimizes the resubstitution error in the resultant clusters (Equations (1)–(3) of Carliles et al. 2010, and references therein). We train a forest of 50 trees on 100,000 randomly selected galaxies from the SDSS spectroscopic sample and regress on our disk galaxy sample to obtain the photo-z estimates shown in Figure 1(c).

Figure 5. Photo-z error as a function of the inclination of the disk galaxies, using the Random Forest approach. In the training procedure the inclinations of the galaxies are included in addition to their four SDSS colors. Compared with Figure 1(c) in which only the SDSS colors are included in the training, the bias is reduced. (A color version of this figure is available in the online journal.)

Given the inclination of disk galaxies to be a parameter which modulates the variance in the photometric sample (Section 3.2), we deduce that the implicit inclusion of the inclination during the training procedure of the Random Forest method would give even better photo-z estimates than the case where only the SDSS colors are used (i.e., Figure 1(c)). Indeed, the photo-z estimates improve, with the resultant bias being 0.0004 and the rms being 0.017. The error in the photo-z versus inclination for this case is shown in Figure 5. It would be interesting to see if other machine learning approaches give similar improvement. For example, although the inclination of a galaxy was not included as a training parameter in the work by Oyaizu et al. (2008), their Artificial Neural Network approach in principle allows for multi-parameter training. It would also be worthwhile to train on other galaxy parameters for comparison, e.g., the morphological parameters as considered in Way et al. (2006, 2009).
5. CONCLUSIONS

The reddening in the spectral energy distribution of a disk galaxy caused by its inclination, if not taken into account, impacts the accuracy of the derived photo-z. We present several approaches to correct the respective property of disk galaxies against the inclination effect. The considered properties are the rest-frame magnitudes, the flux densities of an arbitrary stellar population model for the disk galaxies, and the photo-z. We evaluate the performance of the inclination-dependent color corrections by using the accuracy of photo-z as a diagnostic and find that the corrections give statistically correct face-on colors of the disk galaxies.

We identify the inclination of the disk galaxies to be represented by a low-order PCA mode of the sample, namely the second mode. The inclination therefore modulates significantly the variance in the photometric sample. By considering the first two eigenspectra, the variance is revealed to be related to the reddening effect on the spectral energy distribution. The reddening effect leads to the aforementioned large photo-z error.

Another important question is whether the magnitude corrections (Equations (1)–(5)) are applicable to deriving photo-z that are unbiased with inclination. Using the Random Forest approach, we select from the above training sample face-on only \((b/a = 0.9–1.0)\) galaxies as our new training sample (about 50,000 objects). We train on the uncorrected \(u-g, g-r, r-i, i-z\) colors of this new sample and regress on the corrected colors of our disk galaxy sample. The color corrections are done using Equations (1)–(5) (see the Appendix). If the corrections give correct face-on colors of the disk galaxies, these colors should be fully described by those of the face-on galaxies in the training sample, and the resultant photo-z should be unbiased with inclination. Indeed, we find no inclination dependency in the photo-z error, as shown in Figure 6. The bias and rms are, respectively, 0.002 ± 0.0003 and 0.018 ± 0.0005.

We thank Andrew Connolly, David Koo, Istvan Csabai, Samuel Schmidt, Rosemary Wyse, and Brice Ménard for comments and discussions. We thank the referee for helpful comments and suggestions. We acknowledge support through grants from the W. M. Keck Foundation and the Gordon and Betty Moore Foundation to establish a program of data-intensive science at the Johns Hopkins University.

This research has made use of data obtained from or software provided by the US National Virtual Observatory, which is sponsored by the National Science Foundation.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U. S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org/.

APPENDIX

MAGNITUDE AND COLOR OF INCLINED GALAXIES

The true absolute magnitude, \(M\), of a totally transparent galaxy at any inclination is related to its apparent magnitude, \(m\), as follows:

\[
m - M = 5 \log_{10}(d) - 5 + A_{\text{extrinsic}} + K,
\]

where \(d\), \(A_{\text{extrinsic}}\), and \(K\) are, respectively, the luminosity distance of the galaxy in parsecs, the extrinsic extinction (e.g., the sum of the Galactic and intergalactic extinctions), and the \(K\)-correction. We extend this formula to apply to a circular, dusty disk galaxy at an arbitrary inclination, as follows:

\[
m(b/a) - M(b/a) = 5 \log_{10}(d) - 5 + A_{\text{extrinsic}} + K(b/a).
\]

The extinction intrinsic to the galaxy is composed of two terms, namely, the inclination-independent and -dependent extinctions \(A_{\text{intrinsic}}\) and \(A_{\text{intrinsic}}(b/a)\). They are related to the inclination-dependent absolute magnitude as follows:

\[
M(b/a) = M + A_{\text{intrinsic}} + A_{\text{intrinsic}}(b/a).
\]

Combining Equations (A3) and (A2), we get

\[
m(b/a) - M = 5 \log_{10}(d) - 5 + A_{\text{extrinsic}} + A_{\text{intrinsic}} + A_{\text{intrinsic}}(b/a) + K(b/a).
\]

We derive from Equation (A4) the relation between the face-on and inclined colors, for the \(u, g\) bands here and similarly for the other bands, to be

\[
m_u(1) - m_u = m_u(b/a) - m_u(1) + F_u(b/a) - F_u(1) - [K_u(b/a) - K_u(1)] + [K_u(b/a) - K_u(1)].
\]

The relative extinction is represented by a function of inclination \(F(b/a)\), so that \(M(b/a) - M(1) = A_{\text{intrinsic}}(b/a) - A_{\text{intrinsic}}(1) = F(b/a)\). The choice of \(F(b/a)\) in this work is given in Equation (6) of Section 4. In the application of photo-z estimation, the \(K\)-correction terms are unknown a priori because the spectroscopic redshift of the galaxy in question is unknown. A focus of this work, however, is not the photo-z amplitude but...
the dependency of photo-z error on the inclination. Since our disk galaxies are local, the $K$-corrections are only higher-order modulations to their colors and hence to the photo-z error. We therefore neglect the $K$-correction terms in Equation (A5) and adopt $F_g(b/a) - F_g(b/a)$ (and similarly for the other colors) as the color corrections in the Random Forest case study in Section 4.3. We plan to explore an iterative approach to simultaneously estimate both color corrections and $K$-corrections in the future.

REFERENCES

Adelman-McCarthy, J. K., et al. 2007, ApJS, 172, 634
Adelman-McCarthy, J. K., et al. 2008, ApJS, 175, 297
Bailin, J., & Harris, W. E. 2008, ApJ, 681, 225
Boselli, A., & Gavazzi, G. 1994, A&A, 283, 12
Carliles, S., Budavári, T., Heinis, S., Priebó, C., & Szalay, A. S. 2010, ApJ, 712, 511
Collister, A. A., & Lahav, O. 2004, PASP, 116, 345
Connolly, A. J., Csabai, I., Szalay, A. S., Koo, D. C., Kron, R. G., & Munn, J. A. 1995a, AJ, 110, 2655
Connolly, A. J., Szalay, A. S., Bershady, M. A., Kinney, A. L., & Calzetti, D. 1995b, AJ, 110, 1071
Conroy, C., Schiminovich, D., & Blanton, M. R. 2010, ApJ, 718, 184
Csabai, I., et al. 2003, AJ, 125, 580
Davies, J. I., & Burstein, D. (ed.) 1995, NATO ASIC Proc. 469, The Opacity of Spiral Disks (Dordrecht: Kluwer)
Davies, J. I., Phillips, S., Boyce, P. J., & Disney, M. J. 1993, MNRAS, 260, 491
Disney, M., Davies, J., & Phillipps, S. 1989, MNRAS, 239, 939

Driver, S. P., Popescu, C. C., Tuffs, R. J., Liske, J., Graham, A. W., Allen, P. D., & de Propris, R. 2007, MNRAS, 379, 1022
Giovanelli, R., Haynes, M. P., Salzer, J. J., Wegner, G., da Costa, L. N., & Frei, W. 1994, AJ, 107, 2036
Graham, A. W., & Worley, C. C. 2008, MNRAS, 388, 1708
Holmberg, E. 1958, Meddelanden fran Lunds Astronomiska Observatorium Serie II. 136, 1
Huizinga, J. E., & van Albeda, T. S. 1992, MNRAS, 254, 677
Koo, D. C. 1985, AJ, 90, 418
Madgwick, D. S., Somerville, R., Lahav, O., & Ellis, R. 2003, MNRAS, 343, 871
Maller, A. H., Berlind, A. A., Blanton, M. R., & Hogg, D. W. 2009, ApJ, 691, 394
Marinoni, C., & Buzzi, A. 2010, Nature, 468, 539
Masters, K. L., Giovanelli, R., & Haynes, M. P. 2003, AJ, 126, 158
Masters, K. L., et al. 2010, MNRAS, 404, 792
Oyaizu, H., Lima, M., Cunha, C. E., Lin, H., Frieman, J., & Sheldon, E. S. 2008, ApJ, 674, 768
Padilla, N. D., & Strauss, M. A. 2008, MNRAS, 388, 1321
Ryden, B. S. 2004, ApJ, 601, 214
Shao, Z., Xiao, Q., Shen, S., Mo, H. J., Xia, X., & Deng, Z. 2007, ApJ, 659, 1159
Stoughton, C., et al. 2002, AJ, 123, 485
Unterborn, C. T., & Ryden, B. S. 2008, ApJ, 687, 976
Valentijn, E. A. 1990, Nature, 346, 153
Way, M. J., Foster, L. V., Gazis, P. R., & Srivastava, A. N. 2009, ApJ, 706, 623
Way, M. J., & Srivastava, A. N. 2006, ApJ, 647, 102
Yip, C.-W., Szalay, A. S., Wyse, R. F. G., Dobos, L., Budavári, T., & Csabai, I. 2010, ApJ, 709, 780
Yip, C. W., et al. 2004, AJ, 128, 2603
York, D. G., et al. 2000, AJ, 120, 1579

Driver, S. P., Popescu, C. C., Tuffs, R. J., Liske, J., Graham, A. W., Allen, P. D., & de Propris, R. 2007, MNRAS, 379, 1022
Giovanelli, R., Haynes, M. P., Salzer, J. J., Wegner, G., da Costa, L. N., & Frei, W. 1994, AJ, 107, 2036
Graham, A. W., & Worley, C. C. 2008, MNRAS, 388, 1708
Holmberg, E. 1958, Meddelanden fran Lunds Astronomiska Observatorium Serie II. 136, 1
Huizinga, J. E., & van Albeda, T. S. 1992, MNRAS, 254, 677
Koo, D. C. 1985, AJ, 90, 418
Madgwick, D. S., Somerville, R., Lahav, O., & Ellis, R. 2003, MNRAS, 343, 871
Maller, A. H., Berlind, A. A., Blanton, M. R., & Hogg, D. W. 2009, ApJ, 691, 394
Marinoni, C., & Buzzi, A. 2010, Nature, 468, 539
Masters, K. L., Giovanelli, R., & Haynes, M. P. 2003, AJ, 126, 158
Masters, K. L., et al. 2010, MNRAS, 404, 792
Oyaizu, H., Lima, M., Cunha, C. E., Lin, H., Frieman, J., & Sheldon, E. S. 2008, ApJ, 674, 768
Padilla, N. D., & Strauss, M. A. 2008, MNRAS, 388, 1321
Ryden, B. S. 2004, ApJ, 601, 214
Shao, Z., Xiao, Q., Shen, S., Mo, H. J., Xia, X., & Deng, Z. 2007, ApJ, 659, 1159
Stoughton, C., et al. 2002, AJ, 123, 485
Unterborn, C. T., & Ryden, B. S. 2008, ApJ, 687, 976
Valentijn, E. A. 1990, Nature, 346, 153
Way, M. J., Foster, L. V., Gazis, P. R., & Srivastava, A. N. 2009, ApJ, 706, 623
Way, M. J., & Srivastava, A. N. 2006, ApJ, 647, 102
Yip, C.-W., Szalay, A. S., Wyse, R. F. G., Dobos, L., Budavári, T., & Csabai, I. 2010, ApJ, 709, 780
Yip, C. W., et al. 2004, AJ, 128, 2603
York, D. G., et al. 2000, AJ, 120, 1579