The Color-magnitude Relation of Disk Galaxies

WU Hai-bin, LIU Cheng-ze, ZHANG Bo, CHANG Rui-xiang

1Department of Physics, Shijiazhuang College, Shijiazhuang 050035
2Department of Physics, Hebei Normal University, Shijiazhuang 050016
3Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030

Abstract 15257 face-on disk galaxies are selected from the second group of data released by the Sloan Digital Sky Survey, and their color-magnitude relation is studied statistically. It is shown that the three colors $g - r$, $r - i$ and $r - z$ are each closely correlated with the $r$-band absolute magnitude, i.e., the brighter the galaxies, the redder the colors, and the smaller the dispersion of color indexes. The implications of the observed color-magnitude relations on the star formation history of disk galaxies are briefly discussed.

Key words: galaxies: fundamental parameters (classification, color, luminosity, mass, radius, etc.)—galaxies: abundance—galaxies: formation—galaxies: evolution

1. INTRODUCTION

It is well known that in the multi-dimensional space constructed by the fundamental observational quantities of galaxies, the distribution of galaxies is not uniform and random, i.e., some correlations exist among the observational quantities.

Early in 1959, Baum et al. discovered that the color-magnitude relation exists in the early-type galaxies of the neighboring cluster of galaxies, i.e., the brighter the galaxy, the redder the color\textsuperscript{[1]}. This observational result was further confirmed by later observations\textsuperscript{[2–6]}, and used to constrain the models of the formation and evolution of early-type galaxies. At present, the explanation for the color-magnitude relation of early-type galaxies is: the
brighter the galaxy (i.e., the more massive the galaxy), the higher the metal abundance of its stellar population, therefore the redder the color of the galaxy\(^{6-8}\), but the difference of stellar population ages among various early-type galaxies is very small.

However, the study about the color-magnitude relation of disk galaxies is relatively scarce. Visvanathan et al.\(^{9}\) found that a color-magnitude relation similar to that of early-type galaxies exists also in the early-type spiral galaxies (S0/a\(\sim\)Sab) of the Virgo galaxy cluster, though with a larger dispersion. They believed that the color-magnitude relation of spiral galaxies is probably caused by the variation of the content of young stellar population with the galactic mass. Tully et al.\(^{10}\) found that a color-magnitude relation exists as well in the late-type spiral galaxies. With the photometric and spectral observational data of the 183487 galaxies from the Sloan Digital Sky Survey, Blanton et al.\(^{11}\) divided the galaxies into early-type and late-type galaxies, according to the Sersic index of surface brightness profile obtained by fitting, and found that the color-magnitude relation exists as well in late-type galaxies, but it is much weaker than that of early-type galaxies (refer to Fig.14 of Reference \(^{11}\)).

The main reasons for the scarcity of studies on the color-magnitude relation of disk galaxies are: firstly, the dust content of disk galaxies is relatively rich, as the extinction caused by the dust is different at different wavebands, it has an important influence on the color, and at present we know very little about the properties of the dust; secondly, recent star formation activity exists in disk galaxies, and the emission lines affect as well the color of the galaxy; besides, the stellar population ages of disk galaxies are distributed in a rather wide range, and the joint action of age, metal abundance and dust makes it difficult to infer the property of stellar population from the color.

The Sloan Digital Sky Survey (SDSS) provides a relatively complete sample of galaxies with not only photometric data at 5 wavebands but also some spectral data, so making possible a statistical study on the color-magnitude relation of disk galaxies. The main purpose of this paper is to study statistically the color-magnitude relation of disk galaxies by selecting a sample of face-on disk galaxies from the second data release (DR2, in brief) of SDSS. Compared with the previous studies (especially Reference \(^{11}\)), this study has two features: first, in order to reduce the influence of dust on the color-magnitude relation, we select only the face-on disk galaxies, unlike the previous studies that included late-type galaxies of all spatial orientations. Secondly, a more reasonable criterion (see Section 2.2) is used for the selection of disk galaxies. We may point out that the Sersic index that Blanton et al.\(^{11}\) used to distinguish the early-type and late-type galaxies depends on the model fitting of the surface brightness profile.

2. SAMPLE AND DATA REDUCTION

2.1 A Brief Introduction to SDSS

The CCD photometric system of SDSS adopts the drift-scan technique to make the photometric observations at the five wavebands \(u, g, r, i, z\), and to make the spectral observations on some of these wavebands. The data used in this paper come from the DR2 of SDSS, its photometric measurements cover the 3324\(\text{deg}^2\) northern sky, in which spectral observations are made for about 260000 galaxies\(^{12}\).
The SDSS data provide each source with many photometric parameters and, for sources with spectral observations, many spectral parameters. Of them, this paper uses mainly the following photometric parameters: the Petrosian magnitude, the radius $R_{90}$ at the 90% of the maximum Petrosian flux, the radius $R_{50}$ at the 50% of the maximum Petrosian flux, the ratio of the short and major semi-axes of the galaxy $q = b/a$ (i.e., axial ratio) and the probability fracDEV that the surface brightness profile of the galaxy is of the De Vaucouleurs type, as well as the redshift obtained from the spectral observation. The exact definitions of these observational quantities can be found in References [12-16].

SDSS makes photometric measurements at 5 wavebands, in which the $r$-band is the standard waveband for the photometry processing of SDSS, as well as the reference waveband for selecting the spectral sample. Besides, as the exposure at the $u$-band is too short, the photometric error is relatively large, so instead of the $u$-band photometric data, this paper uses the $r$-band Petrosian magnitude to obtain the absolute magnitude $M_r$ of the galaxy, and studies the variations of the color indexes $g - r$, $r - i$ and $r - z$ with $M_r$.

2.2 The Selection of Sample Galaxies

In order to reduce the influence of dust on the color, this paper selects only the face-on disk galaxies for our study. The adopted two criteria are: (1) fracDEV < 0.2; (2) the axial ratio $q = b/a > 0.75$. The first criterion is used for selecting disk galaxies[6], and the second criterion is used for selecting face-on galaxies and the $r$-band data are used in the selection. Besides, considering that the typical error of the redshift in the SDSS data is 0.004, and that the proper motion of the nearby galaxy will affect seriously the distance derived from the observed redshift and therefore the absolute magnitude, the sources with redshifts less than 0.005 are not included in our sample, and the finally obtained sample consists of 15257 face-on disk galaxies.

Fig.1 gives the statistical histograms for some of the fundamental parameters of the sample. The upper-left panel is the distribution of redshifts, its peak value is located about 0.075; the upper-right panel gives the histogram of the Petrosian half-luminosity radius $R_{50}$ (in arcsec) at $r$-band; the lower-left is the histogram for $C = R_{90}/R_{50}$, and the lower-right is that of the absolute magnitude at $r$-band $M_r$. The parameter $C = R_{90}/R_{50}$ can represent as well the surface brightness profile of a galaxy, the relevant studies indicate that by taking $C = 2.6$ as a dividing line, the galaxies can be roughly divided into the early-type galaxies ($C > 2.6$) and late-type galaxies ($C < 2.6$)[17]. From Fig.1 we can see that almost all of the galaxies in our sample have $C < 2.6$, and this implies that the first criterion proposed by us for selecting disk galaxies is reasonable.

2.3 Data Reduction

To discuss the color-magnitude relation, we have to calculate first the colors and absolute magnitudes of the galaxies, and we shall adopt, for this purpose, the Petrosian magnitude in the SDSS data, calculated from the Petrosian flux. In theory, the Petrosian flux accounts for 80% of the flux of the galaxy with a De Vaucouleurs profile[15]. For studying disk galaxies, it is reliable to describe the total flux of a galaxy by its Petrosian flux. Now, the same photometric aperture (at $r$-band) is used for the Petrosian magnitudes at the 5 wavebands of SDSS, because there is no aperture error, the Petrosian magnitude is most
suitable for calculating the color of the galaxy.

The absolute magnitude $M_r$ of a galaxy is given by the following formula:

$$M_r = m - 5 \log(D_L) - 25 - K(z),$$

in which, $m$ is the visual magnitude at the waveband, $D_L$ is the luminosity distance of the galaxy (in Mpc), $K(z)$ is the $K$-correction. In this paper, the $K$-correction is that given by Blanton et al.\cite{18}, taken from the web address: http://sdss.physics.nyu.edu/vagc, and when calculating $D_L$, the standard cosmological model ($\Omega_0 = 0.3$, $\Omega_A = 0.7$, $h = 0.7$) is used for calculating the distance of the galaxy. In fact, because of the rather low redshifts of our sample galaxies (see Fig.1), different cosmological models make little difference on the results. When calculating the color and absolute magnitude of the galaxy, we make use of the Galactic extinctions at 5 wavebands for each source calculated by Schlegen et al., given in the data release of SDSS.

The color index is generally taken to be a blue magnitude minus a red magnitude, so, a larger color index means a redder color. The magnitudes concerned have to be first corrected for the $K$-correction and the Galactic foreground extinction. In this paper we consider only the variations of the color indexes $g - r$, $r - i$ and $r - z$ with the absolute magnitude $M_r$. 

---

Fig. 1 Histograms of several parameters of our sample galaxies
3. ANALYSIS AND DISCUSSION

Following Shen Shi-yin et al.\cite{19}, the sample is divided into 10 absolute magnitude bins, with each bin having an equal number of sample galaxies. Then, the distribution histogram of color indexes for each bin is fitted by a normal curve, with mathematical expectation $\hat{C}$ and mean square deviation (dispersion) $\sigma$, which are estimated by the maximum likelihood method,

$$f(M_r, \hat{C}(M), \sigma(M))dM_r = \frac{1}{\sqrt{2\pi}\sigma(M)} \exp\left[-\frac{(M_r - \hat{C}(M))^2}{2\sigma^2(M)}\right] dM_r.$$  \hspace{1cm} (2)

Fig. 2 gives the observed distributions of the color index $g - r$ in the different bins of absolute magnitude, and the smooth curves are the best-fitting normal curves by the maximum likelihood method. We can see that for all the bins, the color index exhibits a very good normal distribution. We should mention that the moral distribution is also exhibited by the other two color indexes $r - i$ and $r - z$ in different absolute magnitude bins. For simplicity here we give only the results for the color index $g - r$.

Fig. 3 presents the finally obtained color-magnitude relations of disk galaxies, for the three color indices. In the figure each small dot represents a galaxy, the circles with error bars are the fitting results in the 10 absolute magnitude bins obtained by using the above-mentioned method, of which the $x$-coordinate is the mean absolute magnitude of each bin, the $y$-coordinate is the mathematical expectation $\hat{C}(M_r)$ of the normal distribution of the color index, and the error bar is the dispersion $\sigma(M_r)$, and the straight line is the the least
squares fit to the circles, the equation of fit being given in the figure.

From Fig. 3 we can find that each of the three color indexes is well correlated with the absolute magnitude, in the sense that the brighter the galaxy, the redder the color, and the smaller the dispersion in color. Compared with the color-magnitude relation of late-type galaxies given in Reference [11] (Fig.14), our result tends to be slightly bluer. This is because that our sample galaxies are all face-on disk galaxies (Criterion (2)), with a smaller dust content, while the sample in Reference [11] is composed of late-type galaxies of all spatial orientations. This indicates further that the color-magnitude relation obtained by us is affected very little by dust.

In Fig. 3 the data of the darkest bin indicate that at the dark end the color-magnitude relation of disk galaxies has a tendency to become flat, but the number of observational data of dark galaxies is relatively small and their observational errors are rather large, so this paper can not yet make a definite conclusion on this point. As further data are being released by SDSS, it is hopeful to make a deeper investigation on this question.

Fig. 3 The color-magnitude relations of face-on disk galaxies
About the color-magnitude relation of disk galaxies, so far no convincing and generally agreed explanation is available. The redder color of the galaxy may be caused by an older age of its stellar population, a higher metal abundance, a richer dust content, or three. In other words, the coaction of the dust content, stellar population age and metal abundance makes it very difficult to infer the property of the stellar population in the disk galaxy from its observed color and magnitude. As only face-on disk galaxies are selected in our sample, the influence of dust can be neglected, so the color-magnitude relation obtained by this paper represents basically the different characteristics of the stellar populations in disk galaxies, i.e., the brighter the galaxy, the older the stellar population age, and the richer the metal abundance. This conclusion is consistent also with the magnitude-metal abundance relations of spiral galaxies obtained by other authors\textsuperscript{[20,21].}

Comparing the predictions of galactic semi-analytical model with the results of the photometric observations of 121 spiral galaxies, Bell et al.\textsuperscript{[22]} pointed out that for a brighter (more massive) galaxy, the optical-band color predicted by the model tends to be bluer than the observed, and that for a darker (less massive) galaxy, the predicted optical-band color tends to be redder. They believed that the inconsistency between the model and the observation can hardly be improved by changing the description of the star-formation rate in the model, as star formation history in disk galaxies is dominated by the cooling process of gases, and the current models hold that the radiation cooling of low-mass galaxies is very effective, so the stellar population age predicted by models tends to be older. The result of this paper is consistent with the observational result given by Bell et al., i.e., it also indicates that the stellar population age of massive spiral galaxies tends to be older and the metal abundance tends to be higher, and it presents a challenge to the present models of the formation and evolution of disk galaxies.

4. CONCLUSIONS

We have selected 15257 face-on disk galaxies from the second group of data released by the Sloan Digital Sky Survey, and obtained the absolute magnitudes and color indexes for all the galaxies from their Petrosian magnitudes at 4 wavebands. We divide our sample into 10 bins according to absolute magnitudes, then we fit the distribution histogram of the color indexes of the galaxies in each bin with a normal function, and the color-magnitude relation of disk galaxies is studied statistically using the peak values and dispersions of the fitted normal functions for the bins. The result indicates that the three color indexes \( g - r \), \( r - i \) and \( r - z \) are all correlated closely with the \( r \)-band absolute magnitude: the brighter the galaxy, the redder the color, and the smaller the dispersion of color indexes. This implies that the stellar population age of massive spiral galaxies tends to be older, and that the metal abundance tends to be higher, and this is a very important observational constraint on the existing models of the formation and evolution of disk galaxies.

References

14 Yuan Qi-rong, Zhu Chao-xi, AcASn, 2003, 44, 342
16 Abazajian K., et al., AJ, 2003, 126, 2081