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Color-Redshift Relations and Photometric Redshift Estimations of Quasars in Large Sky Surveys *

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Abstract With a recently constructed composite quasar spectrum and the χ^2 minimization technique, we describe a general method for estimating the photometric redshifts of a large sample of quasars by deriving theoretical color-redshift relations and comparing the theoretical colors with the observed ones. We estimated the photometric redshifts from the 5-band SDSS photometric data of 18678 quasars in the first major data release of SDSS and compared them with their spectroscopic redshifts. The difference is less than 0.1 for 47% of the quasars and less than 0.2 for 68%. Based on the calculation of the theoretical color-color diagrams of stars, galaxies and quasars both on the SDSS system and on the BATC system, we expect that we would be able to select candidates of high redshift quasars more efficaciously with the latter than with the former, provided the BATC survey can detect objects with magnitudes fainter than 21.

Key words: galaxies: photometry — quasars: general — quasars: emission lines – surveys

1 INTRODUCTION

Quasars are intrinsically very luminous objects with absolute magnitudes brighter than $M_V < -23$, but many of them look very faint because they are usually very far away from us. Morphologically, quasars look like stars on photographic and CCD plates and we can not identify them directly from the images. However, the spectrum of a typical quasar usually consists of strong broad emission lines and a power law continuum (Francis et al. 1992; Vanden Berk et al. 2001), which is quite different from star spectra. Therefore it is relatively easy to separate quasars from stars with spectroscopic observations. In recent years, more and more quasars have been discovered along with the ongoing large sky surveys such as SDSS (Sloan Digital Sky Survey), 2dF (2 degree Fields) and BATC (Beijing-Arizona-Taipei-Connecticut). Many of the quasars have large redshifts and therefore are very helpful in the study of the structure and evolution of the early universe.

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Astronomical photometry can be used as low-resolution spectroscopy (Bessell 1990), and photometric observation has the advantage of large samples of objects from large sky areas. It can identify much fainter objects than can spectroscopic observation at the same exposure time. Measuring the redshifts of galaxies and quasars using multi-color photometry has become both very popular and powerful in recent years (Brunner et al. 1997; Connolly et al. 1999; Xia et al. 2002). Among the many current sky survey programs with multi-color photometry, SDSS aims to discover more than 10^6 galaxies and 10^5 quasars (York et al. 2000). The photometry in the SDSS is being done with five passbands (u', g', r', i', z') covering from from 3000Å to 10500Å (Fukugita et al. 1996). Such a 5-band photometry can be treated as an $R \sim 4$ objective-prism survey (Richards et al. 2001). With such photometric data, quasar candidates can be efficaciously selected on prescribed criteria (Fan 1999; Newberg et al. 1999; Richards et al. 2002). Subsequent spectroscopic observations of these candidates have revealed 18678 quasars in the first major data release of SDSS (Abazajian et al. 2003). The discovery of several quasars with redshifts greater than 6.0 in the SDSS work has given us important information about the reionization epoch of our universe (Becker et al. 2001; Fan et al. 2002).

A program of multi-color photometric survey named BATC has been developed in China (Chen 1998; Zhou et al. 2001; Zhou et al. 2003). It is being carried out on the 60/90 cm Schmidt telescope of the National Astronomical Observatories of Chinese Academy of Sciences. It uses a Ford Aerospace CCD with 1024×1024 pixels and 15 intermediate-band filters covering from 3200Å to 10000Å. The field of view of the telescope is about 1 deg^2 and the limit magnitude for photometry is approximately 21.0 in the V band. Because this system possesses more than the usual number of filters, it can obtain much more accurate photometric data such as the spectral energy distributions (SED) of many different types of objects. The survey started work in 1995 and has so far surveyed about 100 deg^2 sky at high galactic latitudes. It has yielded many important results on star clusters, nearby galaxies and galaxy clusters (Kong et al. 2000; Yuan et al. 2001; Ma et al. 2001; Xia et al. 2002).

With its 15-band photometric data, the BATC survey can more efficaciously select quasar candidates than other broad band surveys. In this paper, we first derive some theoretical color-redshift relations for quasars based on the composite quasar spectrum obtained in the SDSS, then use these relations to estimate the photometric redshifts for a large sample of quasars, which are then compared with their spectroscopic redshifts. Furthermore, we shall give the theoretical color-color relations of stars, galaxies and quasars in both on the SDSS system and on the BATC system, and we shall demonstrate that the BATC diagrams should be more efficacious in selecting high redshift quasar candidates than the SDSS diagrams, provided the BATC survey can reach magnitudes fainter than magnitude 21.

2 COLOR-REDSHIFT RELATIONS OF QUASARS IN THE SDSS

Using the spectra for more than 2200 quasars in their Early Data Release, the SDSS team has derived a composite spectrum for quasars (Vanden Berk et al. 2001). Covering the wavelength range from 800Å to 8550Å it is much broader than any previous composite quasar spectrum (Francis et al. 1991; Zheng et al. 1997). Assuming that this composite spectrum is the best representative for all quasars, we can derive the color-redshift relations for quasars for different photometric systems. This means, however, that we have to omit certain types of quasars such as those with broad absorption lines and redder colors in our derivations.

With the assumed composite quasar spectrum, we can estimate the quasar magnitude in any given passband for each given redshift. Let $S(\nu)$ be the transmission efficiency of the filter at frequency ν, and $f(\nu)$ the flux of the quasar at the same frequency, then the flux of the quasar over the passband (ν_1, ν_2) is

$$f = \int_{\nu_1}^{\nu_2} f(\nu)S(\nu)\mathrm{d}\log\nu\,. \tag{1}$$

Because the SDSS system is an AB photometry system (Fukugita et al. 1996), the magnitude in this passband is:

$$m = -2.5\log\frac{\int_{\nu_1}^{\nu_2} f(\nu)S(\nu)\mathrm{d}\log\nu}{\int_{\nu_1}^{\nu_2} S(\nu)\mathrm{d}\log\nu} - 48.60\,. \tag{2}$$

Then the color of this quasar can be expressed as (Richards et al. 2001):

$$m_1 - m_2 = -2.5\left(\log\frac{\int_{\nu_1}^{\nu_2} f(\nu)S_1(\nu)\mathrm{d}\log\nu}{\int_{\nu_1}^{\nu_2} S_1(\nu)\mathrm{d}\log\nu} - \log\frac{\int_{\nu_3}^{\nu_4} f(\nu)S_2(\nu)\mathrm{d}\log\nu}{\int_{\nu_3}^{\nu_4} S_2(\nu)\mathrm{d}\log\nu}\right)\,. \tag{3}$$

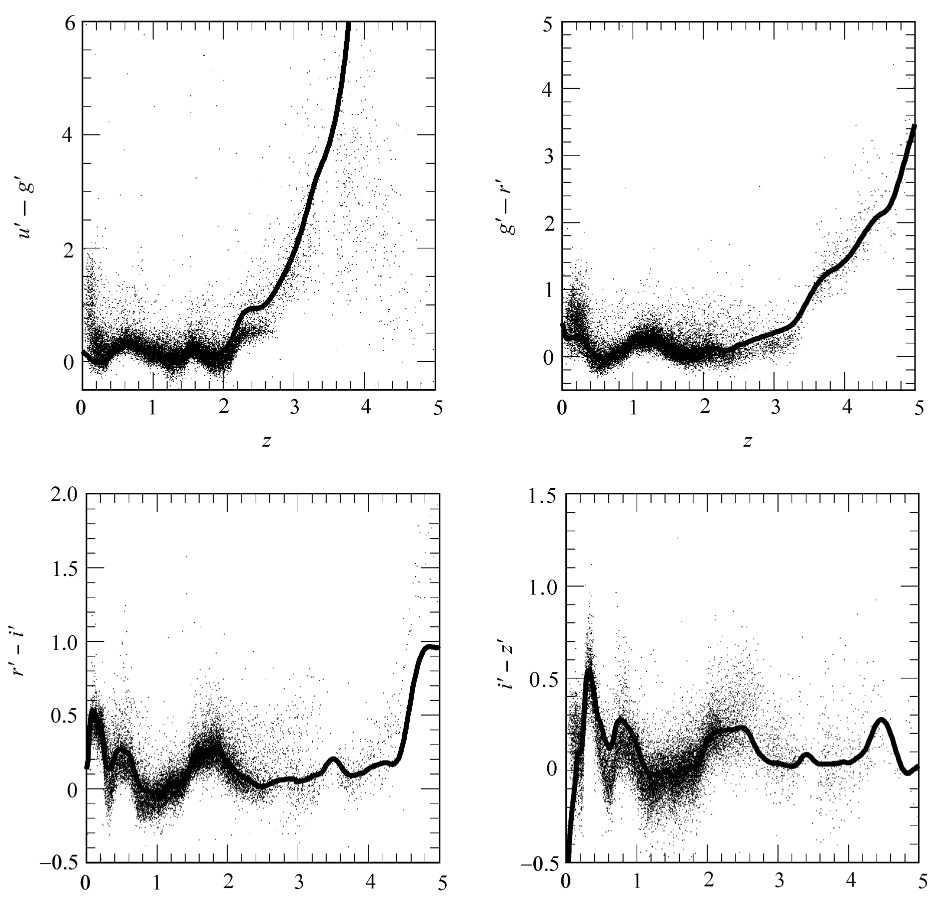

Fig. 1 Theoretical color-redshift relations for quasars on the SDSS system (solid lines), compared to the observed data of 18678 quasars (dots) in the SDSS.

With the transmission curves of the SDSS filters and the composite quasar spectrum, we calculated the magnitudes in the five SDSS photometric bands at different redshifts z and hence the four theoretical color-redshift relations shown by solid lines in Fig. 1. We noticed that we could not obtain reasonable values of the color $u' - g'$ at the larger redshifts, because the Lyα emission line moves outside the range of the filter u' when the redshift exceeds 3.6. We found that our color-redshift relations are very similar to those obtained in Fan (1999) based on a power law continuum and typical quasar emission line ratios. Our method of deriving the relations is more straightforward.

For comparison, we added in Fig. 1 the observational data of 18678 quasars in the first major data release of SDSS (Abazajian et al. 2003); these are shown as dots. It is clear that our theoretical curves agree well with the observed data.

3 ESTIMATION OF PHOTOMETRIC REDSHIFTS OF QUASARS

Photometric redshifts of quasars can be estimated by comparing the observed colors with the theoretical color-redshift relations. A standard χ^2 minimization method is used here to estimate the most probable photometric redshift. If we write the theoretical color as $m_{i,\rm theory} - m_{j,\rm theory}$, the observed color as $m_{i,\rm observed} - m_{j,\rm observed}$ and the uncertainties of the observed magnitudes in the i and j bands as $\sigma_{m_{i,\rm observed}}$, $\sigma_{m_{j,\rm observed}}$, respectively, then χ^2 is defined as

$$\chi^2 = \sum_{u',g',r',i',z'} \frac{[(m_{i,\rm theory} - m_{j,\rm theory}) - (m_{i,\rm observed} - m_{j,\rm observed})]^2}{\sigma^2_{m_{i,\rm observed}} + \sigma^2_{m_{j,\rm observed}}} . \tag{4}$$

The summation is over the four colors corresponding to the five passbands (see a qualification below). For a given quasar we thus obtain a sequence of χ^2 values for redshifts between 0.0 and 5.0. If we further consider that all quasars should have absolute magnitude brighter than –23, then we can exclude some unreasonably low redshifts.

In the sequence of χ^2 values, we identify the redshift corresponding to the smallest χ^2 value as the photometric redshift for the given quasar on the basis of its 5-band photometric data. In this way we have found the photometric redshifts for all the 18678 SDSS quasars. As noted above, the Lyα emission line moves out of the range of the filter u' when the redshift is larger than 3.6, so we would get unreasonable values of the color $u' - g'$ at larger redshifts. This means that we can only use 3 out of the 4 colors for redshifts beyond 3.6. For redshifts below 3.6, we use all the four colors.

The spectroscopic redshifts of all the 18678 quasars have been given (Abazajian et al. 2003). With these redshifts, we can check the efficacy of our method. A comparison of the photometric redshifts and the spectroscopic redshifts is shown in Fig. 2. We found that the differences are less than 0.1 for 46.62% of the quasars and less than 0.2 for 67.87%. The histogram of Fig. 3 shows more clearly that our estimated photometric redshifts are accurate to $|\Delta z| \leq 0.2$ for most of the quasars.

In some cases, however, the above method can also lead to wrong results. If the real spectrum of the quasar is substantially different from the composite spectrum or if the uncertainties of the photometric magnitudes are unusually large, then our calculated χ^2 might reach minimum at a wrong redshift. Some examples of such cases are shown in Fig. 4, where the minimum χ^2 clearly occurs at a wrong photometric redshift. This problem can be alleviated if we have more composite spectra available for different types of quasars when calculating the theoretical color-redshift relations.

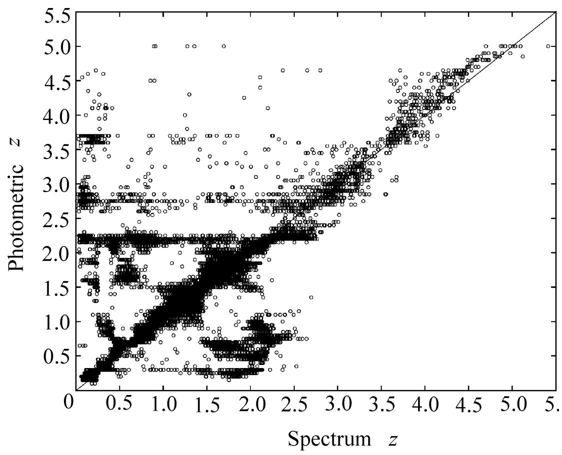

Fig. 2 A plot of photometric redshifts versus spectroscopic redshifts for 18678 quasars in the SDSS data.

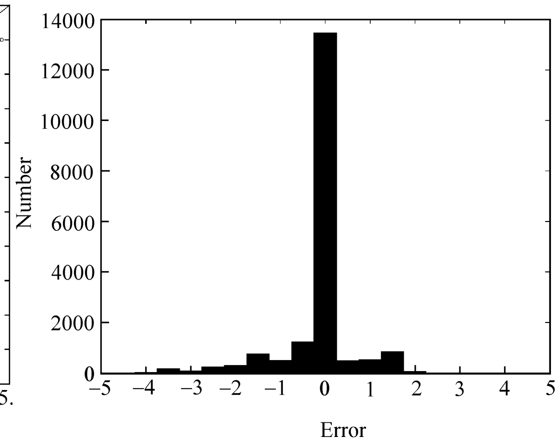

Fig. 3 Histogram of Differences between photometric and spectroscopic redshifts.

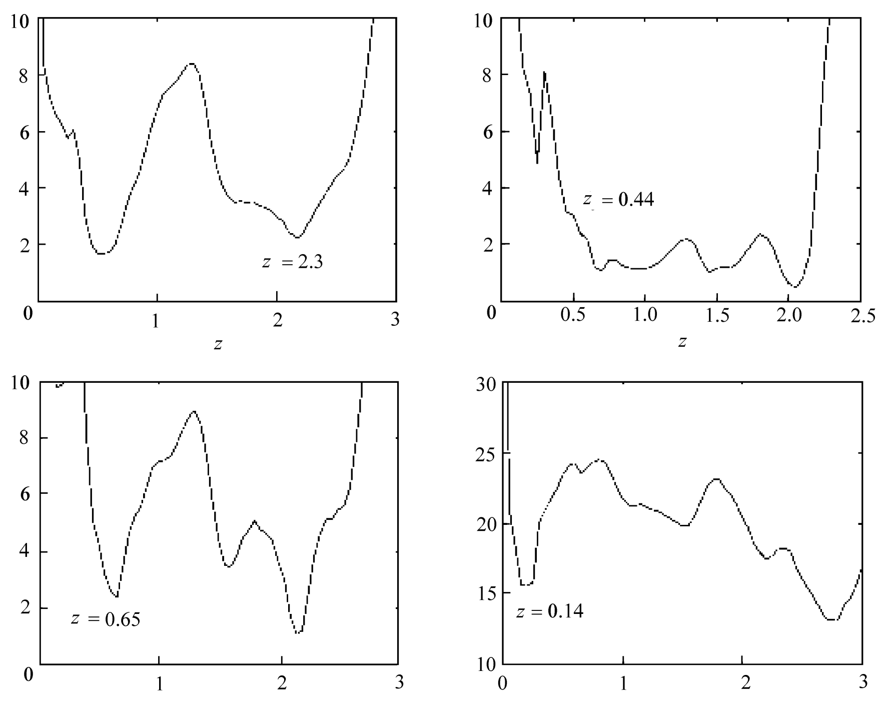

Fig. 4 Four examples of incorrect identification of photometric redshift by the χ^2 minimization method. The spectroscopic redshifts of the quasars are indicated.

The SDSS team has also made estimations of photometric redshift for 2625 quasars in the early data release of SDSS (Richards et al. 2001). They adopted a different method from us when deriving the color-redshift relations. As described in Richards et al. (2001), their color-redshift relations were the median relations for 2200 quasars in their data. They then calculated the photometric redshifts for 2625 quasars using the χ^2 minimization method with the median relations and the observed colors and their result is that 55% of the quasars had differences between the photometric and spectral redshifts less than 0.1, and 70%, less than 0.2. Thus, in this instance, their method appears to be slightly more efficacious than ours. However, ours has the great advantage in that it can be easily adapted to any other photometric system: as soon as the transmission curves of the filters are known, the color-redshift relations are obtained. In contrast, the median color-redshift relations used by the SDSS team can only be used for the SDSS photometric data. We may also note that the efficacy of our photometric redshift estimation is comparable to that in some other groups such as Hatziminaoglou et al. (2000) and Wolf et al. (2001), who estimated the photometric redshifts of smaller samples of quasars using different methods.

4 COLOR-COLOR DIAGRAMS OF QUASARS, STARS AND GALAXIES

We used the method described above to calculate the theoretical colors of quasars, stars and galaxies in the BATC system in order to find some criteria for selecting quasar candidates from the survey data. The transmission curves of the 15 BATC intermediate filters (labelled from a to p, skipping l) are shown in Fig. 5 (see also Xia et al. 2002). We calculated 14 color-redshift relations for quasars in the BATC system using the SDSS composite quasar spectrum. The results are shown in Fig. 6. For stars, we used the stellar spectral library given by Pickles et al. (1998), which contains 130 template spectra of stars with spectral types from O to M. For galaxies, we used the template spectra of 12 types of galaxies (Kinney et al. 1996). We calculated the colors of each type of galaxy at different redshifts from 0.0 to 5.0 at steps of 0.05.

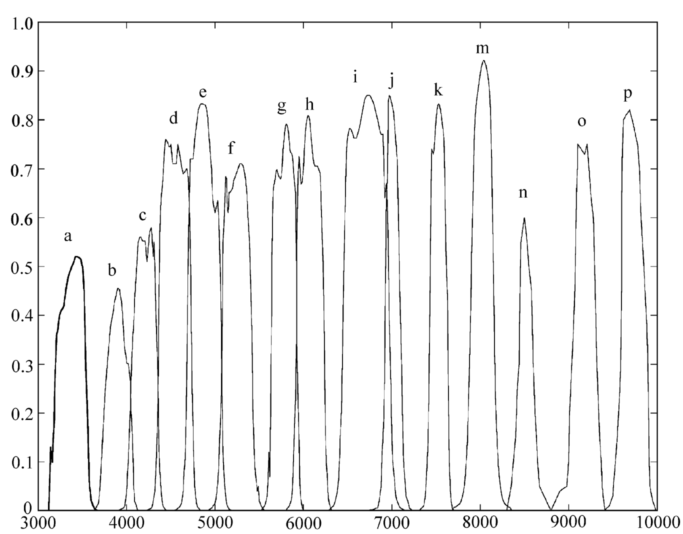

Fig. 5 Transmission curves of 15 intermediate band filters in the BATC survey. The name of each filter is marked on top of each curve.

We have plotted stars, galaxies and quasars on 13 color-color diagrams and found that, in many of the diagrams, it was not easy to use a simple criterion to separate the quasars from the stars. However, on four of the diagrams, it seems possible to separate quasars (especially high redshift ones) from stars and galaxies (see Fig. 7). It is noticeable that most of the stars lie in a narrow belt, while the galaxies with different redshifts are distributed much widely. It is clear that the right upper regions in these diagrams are dominated by high redshift quasars. Therefore, the dashed lines in the four diagrams can be used as simple criteria to select candidates of quasars with redshifts larger than 3.5 in BATC photometric data. Explicitly, the criteria are:

$$b - c > 1.4 \quad \text{and} \quad c - d > 0.4;$$

$$\text{or} \quad c - d > 1.4 \quad \text{and} \quad d - e > 0.4;$$

$$\text{or} \quad d - e > 1 \quad \text{and} \quad e - f > 0.4;$$

$$\text{or} \quad e - f > 1.2 \quad \text{and} \quad f - g > 0.4\,.$$

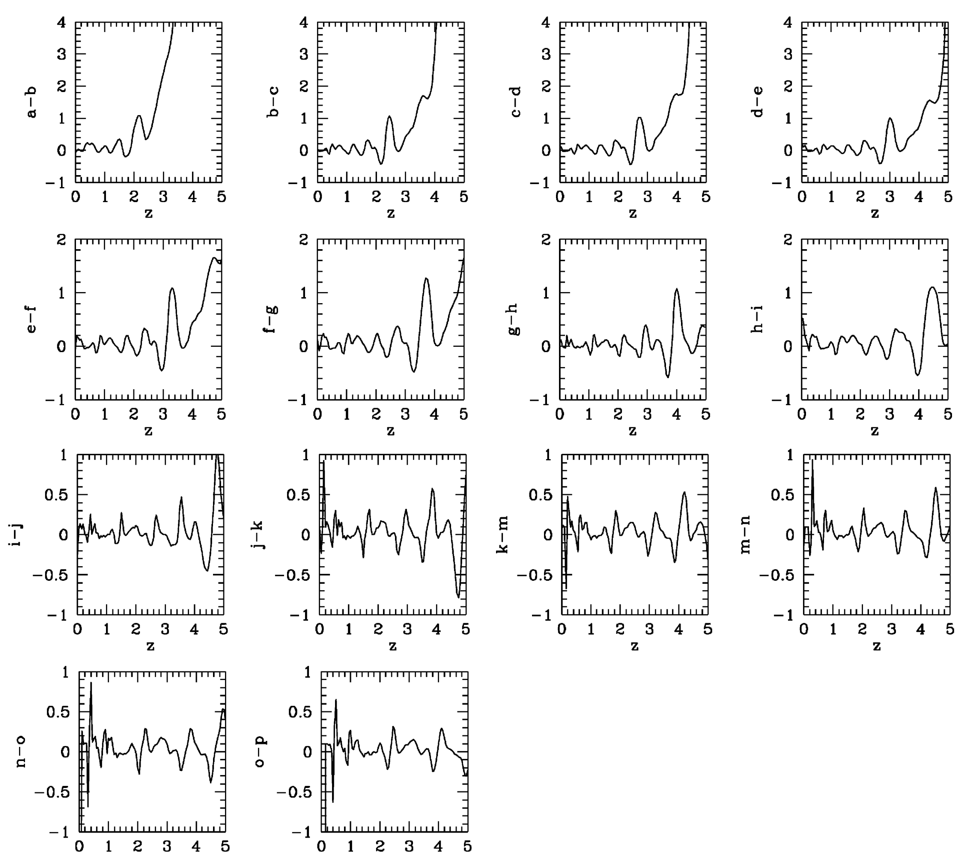

Fig. 6 Theoretical color-redshift relations of quasars in the BATC system.

In addition, it is well known that quasars are mostly point sources while many galaxies are extended objects. Therefore, we can further exclude some galaxies using morphology information. After passing the morphological sieve, high redshift quasar candidates can be selected from these color-color diagrams for further spectroscopic identifications. It should be noted that quasar candidates so selected may still be contaminated with brown dwarfs or some other kinds of AGNs (Fan et al. 2002). Further detailed studies on the differences between brown dwarfs and high redshift quasars in the color-color diagrams may be helpful here.

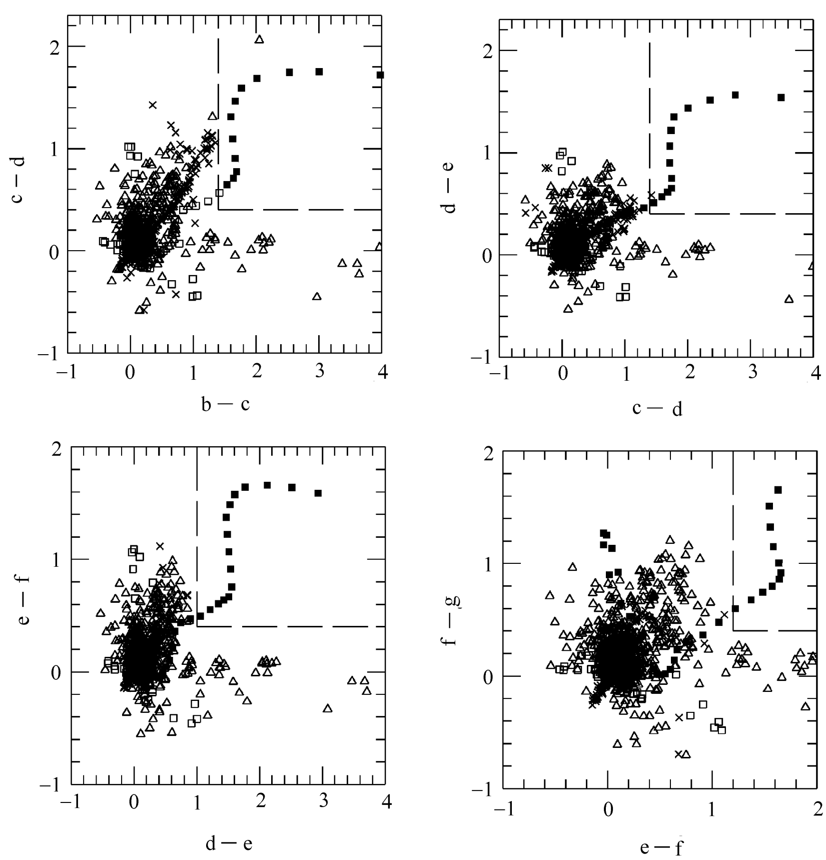

Fig. 7 Four theoretical color-color diagrams of stars, galaxies and quasars in the BATC system. The crosses denote stars and the triangles denote galaxies. The filled and open squares denote quasars with redshifts larger and smaller than 3.5. The region to the right and above the dashed line in each diagram is dominated by high redshift quasars.

With our selection criteria we will still miss many quasars, especially those with lower redshifts because they may be located at the same places as stars in the color-color diagrams. However, a high efficiency of selecting high redshift quasars from these color-color diagrams is attractive, and for this, the BATC photometric system on advantageous because it has 15 intermediate band filters and so is able to identify the main emission lines more accurately than the other broad band photometric surveys. Following the same method as above, we also constructed the color-color diagrams of stars, galaxies and quasars in the SDSS system. The results are shown in Fig. 8; they are similar to those obtained by Fan (1999). Compared to the BATC diagrams, we found that, here, the separation of quasars from stars and galaxies is not so good. Even though high redshift quasars can possibly be selected from the two SDSS diagrams, $(r' - i')$ vs $(g' - r')$ and $(i' - z')$ vs $(g' - r')$, the contamination by stars and galaxies is much more serious. This is understandable because of the broader filter bands in the SDSS photometric system. Therefore, candidates of high redshift quasars are more efficiently found from the BATC photometric data than from the SDSS photometric data.

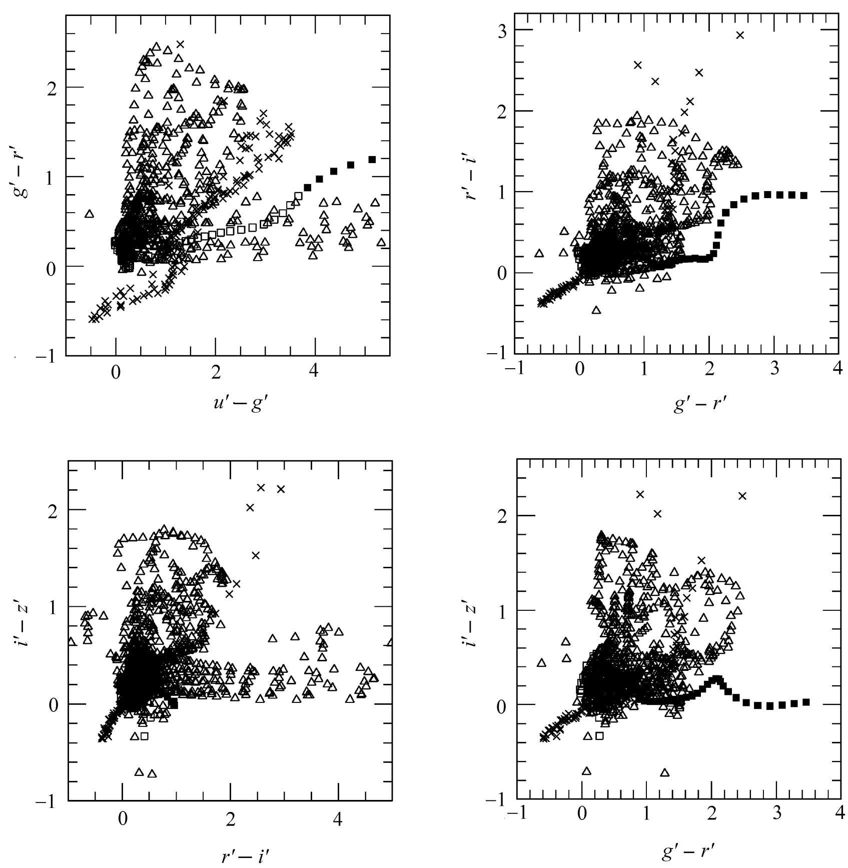

Fig. 8 Four theoretical color-color diagrams of stars, galaxies and quasars in the SDSS system. The crosses denote stars and the triangles denote galaxies. The filled and open squares denote quasars with redshifts larger and smaller than 3.5.

5 DISCUSSION

We have described a method for deriving color-redshift relations of quasars from composite quasar spectrum and applied this method to the SDSS and BATC systems. Our estimated photometric redshifts of the 18687 quasars given in the first major data release of SDSS agree well with their spectroscopic redshifts. This method can be easily adapted to other multi-color survey systems because it only requires the transmission functions of the filters and the photometric data. By comparing the theoretical color-color diagrams of stars, galaxies and quasars in the SDSS and BATC systems, we found the BATC would be better than the SDSS in selecting high redshift quasar candidates, provided the BATC survey can go as deep as SDSS to detect objects fainter than magnitude 21. A detailed comparison of the photometric redshifts, estimated from both the SDSS and BATC photometric data, for quasars in several sky fields common to both surveys will be given in another paper.

All the calculations of photometric redshifts in this paper are based on the composite spectrum of SDSS quasars. However, when we use this composite spectrum for all quasars, there must be some large errors, for the spectra of quasars are in fact quite diverse. For example, the continuum and emission line intensity are different in radio loud and radio quiet quasars (Francis et al. 1993; Zheng et al. 1997). Quasars with broad absorption lines and redder quasars have very different spectra from normal ones (Sprayberry & Foltz 1992; Richards et al. 2003). These differences should be considered when estimating photometric redshifts. In our future work we will use different composite spectra for quasars of different types. In addition, we note that the calculation of minimum χ^2 could be improved with the ASQ method developed recently by the SDSS team to give more accurate quasar photometric redshifts (Budavari et al. 2001).

Large sky area surveys have become very popular in recent years. The huge amount of data obtained from these surveys such as SDSS and 2DF has already provided us much information about the structure and evolution of the universe. Compared to spectroscopic surveys, multi-color photometric surveys over large sky areas can yield the spectral energy distributions of many more fainter objects. With the technique of photometric redshift determination, we can construct large samples of objects with estimated redshifts and perform many interesting studies on galaxies and quasars. Multi-color photometric data can also be used to estimate the spectral types of many stars. From multi-color photometric observations we can efficiently select candidates of galaxies, quasars and some specific type of stars and compile input catalogues for further spectroscopic surveys. This is very important especially for LAMOST, a spectroscopic survey project now in progress in China (Luo & Zhao 2001).

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References

Abazajian K., Adelman-McCarthy J. K., Agueros M.A. et al., 2003, AJ, 126, 2081
Becker R. H., Fan X., White R. L. et al., 2001, AJ, 122, 2850
Bessell M. S., 1990, PASP, 102, 1181
Brunner R. J., Connolly A. J., Szalay A. S., Bershady M. A., 1997, ApJ, 482, L21
Budavári T., Csabai I., Szalay A. S. et al., 2001, AJ, 122, 1163
Chen J.-S., 1998, Proceedings of the 179th IAU Symposium, 123
Connolly A. J., Budavari T., Szalay A.S. et al., 1999, in ASP Conf. Ser. 191, 13
Fan X., 1999, AJ, 117, 2528
Fan X., Narayanan V. K., Strauss M. A. et al., 2002, AJ, 123, 1247
Francis P. J., Hewett P. C., Foltz C. B. et al., 1991, ApJ, 373, 465
Francis P. J., Hewett P. C., Foltz C. B., Chaffee F. H., 1992, ApJ, 398, 476

Francis P. J., Hooper E. J., Impey C. D., 1993, AJ, 106, 417
Fukugita M., Ichikawa T., Gunn J. E. et al., 1996, AJ, 111, 1748
Hatziminaoglou E., Mathez G., Pello R., 2000, A&A, 359, 9
Kinney A. L., Calzetti D., Bohlin R. C. et al., 1996, AJ, 467, 38
Kong X., Chen J., Cheng F. et al., 2000, AJ, 119, 2745
Luo A.-L., Zhao Y.-H., 2001, Chin. J. Astron. Astrophys., 1, 563
Ma J., Zhou X., Kong X. et al., 2001, AJ, 122, 1796
Newberg H. J., Richards G. T., Richmond M., Fan X., 1999, ApJS, 123, 377
Pickles A. J., 1998, PASP, 110, 863
Richards G. T., Weinstein M. A., Schneider D. P. et al., 2001, AJ, 122, 1151
Richards G. T., Fan X., Newberg H. J. et al., 2002, AJ, 123, 2945
Richards G. T., Hall P. B., Vanden Berk D. E., et al., 2003, AJ, 126, 1131
Sprayberry D., Foltz C. B., 1992, ApJ, 390, 39
Vanden Berk D. E., Richards G. T., Bauer A. et al., 2001, AJ, 122, 549
Wolf C., Meisenheimer K., Röser H.-J. et al., 2001, A&A, 365, 681
Xia L. F., Zhou X., Ma J. et al., 2002, PASP, 144, 1349
York D. G., Adelman J., Anderson J. E. Jr. et al., 2000, AJ, 120, 1579
Yuan Q., Zhou X., Chen J. et al., 2001, AJ, 122, 1718
Zheng W., Kriss G. A., Telfer R. C. et al., 1997, ApJ, 475, 469
Zhou X., Chen J., Xu W. et al., 1999, PASP, 111, 909
Zhou X., Jiang Z. J., Xue S. J. et al., 2001, Chin. J. Astron. Astrophys., 1, 372
Zhou X., Jiang Z., Ma J. et al., 2003, A&A, 397, 361