The Processing and Classification for the Spectra of Six Comets [†][⋆]

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Abstract In order to explore the relationship between comets and asteroids, the spectra of six comets, including 78P, C/2009 P1, 49P, C/2010 G2, C/2010 S1, and C/2011 F1, have been observed with the 2.16 m telescope at the Xinglong Observing Station of National Astronomical Observatories. At the same time, the spectra of some sun-like stars are also observed. The IRAF (Image Reduction and Analysis Facility) software is used to process the obtained spectra, and to obtain the relative reflectance spectra of the six comets. Then, they are compared with the 24 asteroid spectral types of the Bus-DeMeo taxonomy to derive the spectral distances of these comets. According to the order of the calculated spectral distances, the details of the reflectance spectra, as well as the results of the K-S test, the asteroid spectral types which are most close to the spectra of these comets are finally determined.

Key words: comets: individual—techniques: spectroscopic—methods: data analysis

1. INTRODUCTION

Internationally, the spectral classification of asteroids has been well developed, now the rather mature classification is the Bus-DeMeo taxonomy based on the data of SMASS II (Small Main-belt Asteroid Spectroscopic Survey II) of the Planetary Spectroscopy Group at MIT (Massachusetts Institute of Technology), which classifies the asteroids into 24 types

according to their spectroscopic characteristics[1]. At present, the work on the spectral classification of comets is relatively rare, one of the reasons is the complexity of the comet's composition, at a short distance from the sun, there will be the structures such as the coma, comet tail, and so on. The spectroscopic characteristics may differ with different structures[2].

However, from the analysis on the cometary spectra, we can learn about the chemical properties of comets. More importantly, the relationship between comets and asteroids can be studied. At present, it is known that some asteroids are the so-called "dead comets", namely the remains of comets after their ejected matter was exhausted, for example, the parent of the Twins meteoric shower, one of three well-known big meteoric showers, is not a comet, but the No.3200 asteroid Phaethon, actually, a dead comet[3].

Recently, the hot points in the research of cometary spectra are mainly concentrated in the following aspects:

(1) Comets and Kuiper belt objects. Although it is commonly believed that the short-period comets are originated from the Kuiper belt, but the specific relationship between the comets entered into the inner solar system and the Kuiper objects far beyond the Neptune's orbit is not yet clear. The recent observations indicate that the color of comets tends to be bluer than the Kuiper belt objects, the lack of red color is a significant difference. If comets come from the Kuiper belt, then the two sorts of objects should have similar characteristics. Jewitt suggested that after a comet entered into the inner solar system, the ejection of the ancient matter covered on its surface causes the color difference between the two[4].

(2) Comets and Centauri asteroids. The Centauri asteroids belong to a sub-category of asteroids, which have no stable orbits and finally are moved away from the solar system by the giant planets. They behave as like asteroids in half, and as like comets in another half. Hence they are named after "Centaurus". The orbits of the Centauri asteroids will penetrate or have penetrated the orbit(s) of one or multiple gaseous giant planets, with a dynamical life of several million years.

Up to 2008, two Centauri asteroids (Chiron and Echeclus) have been discovered with coma activities, so they belong to not only asteroids but also comets. The orbit of the comet 166P/NEAT is very close to the type of Centauri asteroids. And some other Centauri asteroids, such as Okyrhoe, are suspected to have the activities similar with those of comets[5].

(3) Main-belt comets. Main-belt comets are the objects distributed within the main belt of the asteroid belt, but exhibit the activities and characteristics of comets as they move to some positions. Different from the orbits of most comets, which are chiefly at the distances close to Jupiter or far away from the sun, the orbits of the main-belt comets are nearly circular, and within the main belt of the asteroid belt, hence it is very difficult to discriminate them from many standard asteroids by their orbital characteristics. Although the orbital semi-major axes of some short-period comets are within the Jupiter's orbit, but they differ from the main-belt comets, because the orbital eccentricities and inclinations of the main-belt comets are similar with those of the asteroids within the main belt. The three main-belt comets known most early are all positioned in the inner side of the outer edge of the main belt.

So far, we do not know whether these comets come from the Kuiper belt, and how did they change their orbits under the relatively weak gravitational disturbances of planets to

become the main-belt comets of low orbital eccentricity, as like the typical asteroids. Hence, the main-belt comets are assumed to be different from the other comets, they formed in the inner solar system at the positions close to their present positions, like the asteroids of pure ice. Now, it is known that the components of many asteroids include ice, this is good evidence to this theory[6].

We have observed the spectra of six comets and made an analysis, the six comets are 78P, C/2009 P1, 49P, C/2010 G2, C/2010 S1, and C/2011 F1.

The orbit perihelions of the comets 49P and 78P are close to Mars, and the aphelions are close to Jupiter, they are all periodical comets. The periodical comets originate from the Kuiper belt, hence their precursor objects are the Kuiper-belt objects. And the Centauri asteroids are the transitional bodies between the Kuiper-belt objects and the periodical comets. Therefore, the two comets are closely related with both the Centauri asteroid and the Kuiper-belt object, to analyze the similarity between their spectra and the asteroid spectral types is very meaningful.

The other four comets are all non-periodical comets, should be originated from the Oort cloud. The Oort cloud is too far to observe directly, nobody has studied directly the relationship of Oort cloud objects with comets or asteroids. But it does not mean that the non-periodical comets are irrelevant to asteroids, because some non-periodical comets may become periodical comets under the gravitational perturbations of the giant planets and the sun, and finally evolve to be the dead comets with the characteristics of some kinds of asteroids. Hence, to study the relationship between non-periodical comets and asteroids is meaningful. At the same time, the non-periodical comets are numerous, they should be taken into consideration when we study the spectral types of comets.

Taking the data of the 24 asteroid spectral types of the Bus-DeMeo taxonomy as the module, we have the obtained cometary spectra compare with the module, to obtain the most possible spectral types of these comets, and to make further discussions.

2. OBSERVATIONS

On 28th∼29th Oct. 2011, 3rd∼4th and 4th∼5th Jan. 2012, using the low-dispersion Cassegrain spectrograph of the 2.16 m telescope at the Xinglong Observing Station of National Astronomical Observatories, we made the spectral observations on the six comets 78P, C/2009 P1, 49P, C/2010 G2, C/2010 S1, and C/2011 F1. The low-dispersion grating with the dispersion of 200 Å/mm was adopted, the slit width was $3''$, the central wavelength was $6\,000$ Å, the wavelength range was $2500∼8500$ Å. In which, 78P was observed at different times for three times, 49P was observed for 2 times, C/2010 G2 was observed for 2 times, totally 10 observations were made for the six comets.

The spectral components of comets are rather complex, at a distance close to the sun, there will be coma, cometary tail, and other structures. The spectral characteristics differ with the different structures. Because of the limited power of the telescope for the spectral observation, we cannot observe very weak objects. Among the six comets, C/2009 P1 is brighter, with the magnitude of 8.5 mag, the rest five comets are relatively dark, in the range of 12∼16 mag, the cometary nuclei are apparently enclosed with cometary hairs, hence what we obtained are mainly the reflection spectra of cometary hairs.

Another speciality of cometary spectra is that the comet itself does not emit, it forms a reflection spectrum by reflecting the sunshine, thus besides the information of the comet itself, the cometary spectrum contains also the information of the solar spectrum. In the spectral processing, we have to remove the solar spectrum before obtaining the really useful information. To obtain directly the solar spectrum is difficult, the common-used method is to replace it with the spectrum of one or two selected sun-like stars, the criterion for the selection is that during the observation, the zenith angle of the star is as close as possible to the zenith angle of the target source. The common-used sun-like stars are Hyades 64 (HD28099) and Cyg B (HD186427).

We photographed the spectrum of an He-Ar lamp as the standard for the wavelength calibration. Since that we need only to obtain the relative reflectance spectrum, the absolute flux calibration is unnecessary, so in principle, we need not to photograph the spectrum of the flux calibrator. But considering the other possible uses of the data in the future, we photographed as well the spectrum of the flux calibrator.

The comet moves quite fast in the sky, hence in the process of exposure, the telescope should be adjusted according to the motion of the comet, to guarantee the comet image falling on the slit center of the grating always.

Table 1 gives the details of our observations.

Table 1   The details of observations

	Target	Visual magnitude/mag	Observational time (UT)	Air mass	Heliocentric distance/au	Geocentric distance/au
I	C/2009 P1	8.5	11:00	1.52	1.73	1.98
	16 Cyg B	6.25	11:15	1.07	/	/
	78P	12	14:00	1.31	2.10	1.24
II	78P	12.5	11:30	1.35	2.01	1.79
	C/2010 G2	12	14:00	1.37	2.46	1.81
	Hyades 64	8.1	16:30	1.35	/	/
	49P	16	18:00	1.70	1.65	1.09
III	78P	12.5	11:30	1.35	2.01	1.80
	C/2010 S1	15	12:30	1.27	6.86	6.77
	C/2010 G2	12	13:30	1.33	2.47	1.83
	Hyades 64	8.1	15:30	1.19	/	/
	49P	16	18:00	1.70	1.66	1.08
	C/2011 F1	15	21:30	1.18	4.54	4.49

I: 2011-10-28∼29, clear, no seeing and humidity were recorded because the observational time was lent from others, 16 Cyg B was selected as the sun-like star;
II: 2012-01-03∼04, clear, seeing 4.5″, humidity 40%, Hyades 64 was selected as the sun-like star;
III: 2012-01-04∼05, clear, seeing 2.5″, humidity 40%, Hyades 64 was selected.

3. SPECTRAL PROCESSING

The data of our spectral observations were processed by using the IRAF software under the Linux environment, the procedures are as follows:

(1) Background subtraction: the background indicates the baseline of the electric charges recorded by the every pixel on the CCD surface, also called as zero-second exposure, which is determined by the magnitude of grid voltage. We will take pictures of the background data at the beginning and end of the observation. The first step of the spectral processing is to subtract this background.

(2) Flat-field correction: the quantum efficiency of the every CCD pixel differs, thus the spectral image produced by the CCD will be non-uniform in brightness, this must be corrected by the measurement of flat-field. At the beginning and end of the observation, we will take pictures of flat-field. The process of flat-field correction can be divided into three steps: at first, all the flat-field images are merged into a flat-field file (Flat.imh), then, to make the 3-order spline fitting and normalization on it, and finally, taking this as a reference, to make the subtraction for all the target images.

(3) Cosmic-ray deletion: in the exposure process on the observing target, cosmic rays will unavoidably appear on the background of the CCD. Their number depends on the exposure time, and their positions of appearance are random, they are unfavorable for the subsequent process. The characteristics of cosmic rays are very distinct: the signal intensity is very strong, but the number of occupied pixels is extremely small, even as small as only one pixel, and the surrounding signals are generally very weak, hereby, we can have them deleted.

To this step, we have finished the preprocessing on the spectrum.

(4) Extracting the one-dimensional spectrum: the original spectral image we obtained is of two dimensions, it needs to be converted into a one-dimensional spectrum. According to the position on the slit when the comet was photographed, the corresponding aperture range in the direction of vertical axis is determined, which generally corresponds to the bright strip region in the middle of the vertical axis. The concrete operation depends on the image, the basic principle is to guarantee that most information of the target source is included in this region, and the background skylight is included as least as possible. The next step is the deletion of skylight, as the spectrum contains the skylight component, we have to select two regions on the left and right sides of the spectrum center, which basically contain skylight only, and to subtract the skylight from the signals with a fitting method according to the concrete conditions. Thus, a diagram showing the relation between the signal intensity and the pixel position is obtained. With the same parameters, we extract the one-dimensional spectra of the sun-like star (with the skylight subtracted), and the He-Ar lamp (no need to subtract the skylight).

In actual observations, the zenith angles of different target sources are hardly consistent, hence we need to make the correction of atmospheric extinction, for which the mean extinction coefficients, namely the data file baoextinct.dat, of the Xinglong Observing Station of National Astronomical Observatories is adopted.

(5) Wavelength calibration: to select a few spectral lines with known wavelengths from the spectrum of the calibration lamp, which are easy to recognize, and uniformly distributed between the red end and the blue end of the spectrum, to measure and record the corresponding horizontal coordinates of these spectral lines in units of pixel, then by interpolating and fitting, to scale all the spectral lines, and therefore to obtain the correspondence between the horizontal coordinate and the wavelength. It is necessary that the points with over large variances should be deleted, and to redo the interpolation and fitting. Then, by comparing the spectra of both the target source and the sun-like star with the lamp spectrum of which the wavelength calibration has been made already, to convert the horizontal coordinates of their original spectra into wavelengths, and therefore to obtain the relation between the signal intensity and the wavelength.

Fig.1 shows the one-dimensional spectrum of a target source after making the wave-

length calibration. The horizontal coordinate represents wavelength, the vertical coordinate represents the integrated ADU (Analog/Digital Unit) reading. It is similar for the spectra of other target sources.

It is noteworthy that on the continuum background of the spectrum, a few strong absorption lines exist in the wavelength range of 6500~8000 Å. These absorption lines are not caused by the target source itself, but caused by the absorption of water (oxygen) molecules in the atmosphere through which the light from the target source is penetrated.

(6) Normalization: compared with the visual magnitude of the sun-like star, the visual magnitude of a comet may have a very large difference, it is the same for the spectral flux, but what we are interested in is the profile of the continuum, hence the cometary spectrum and stellar spectrum are all normalized. The general approach is to define the flux at the wavelength 5500 Å (the central wavelength of V-band photometry) to be 1, then to divide the whole spectrum by the flux at this wavelength, thus a diagram of normalized spectral flux is obtained. Fig.2 shows the relative intensity diagram of the spectrum of the comet C/2010 G2 after being normalized by using the flux at the wavelength 5500 Å. It is similar for other target spectra.
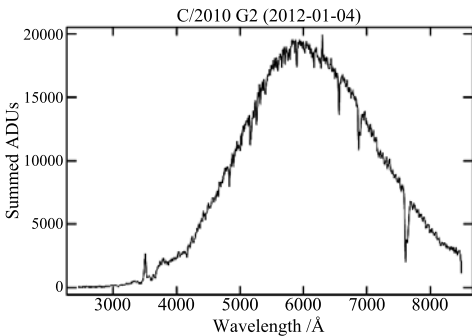

Fig. 1   An example of a target's one-dimensional
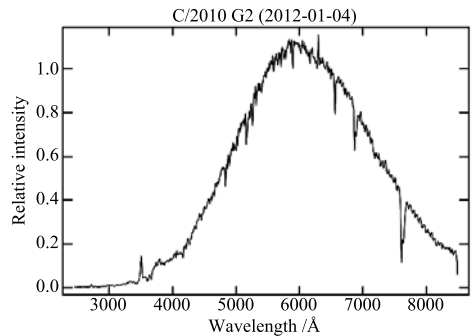spectrum after wavelength calibration

Fig. 2   The relative spectral intensity of the
comet C/2010 G2 after normalization

(7) To obtain the relative reflectance spectrum: to divide the normalized cometary spectrum by the normalized spectrum of the sun-like star, the finally obtained ratio spectrum is the relative reflectance spectrum. In order to show better the spectral profile, the 5-point sliding average is adopted for the final spectrum. This is the final step of our spectral processing. Figs.3~12 display the relative reflectance spectra of the six comets obtained from totally 10 observations. The horizontal coordinate represents wavelength, the vertical coordinate represents the relative reflectance in the range of 0.5~1.5. Here only the wavelength range of 4000~8000 Å is intercepted, in which the CCD has a good response. Still, at a few places the strong absorption lines caused by the atmosphere can be seen clearly, especially at the place around 7500 Å.

4. SPECTRAL DISTANCES

After the relative reflectance spectra of all the comets are obtained, adopting the concept of
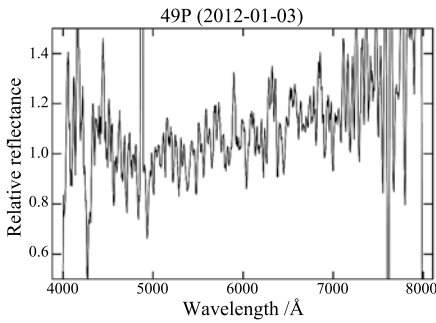
Fig. 3 The relative reflectance spectrum of the comet 49P on 3rd Jan. 2012
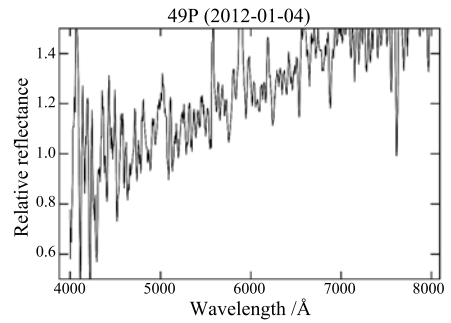

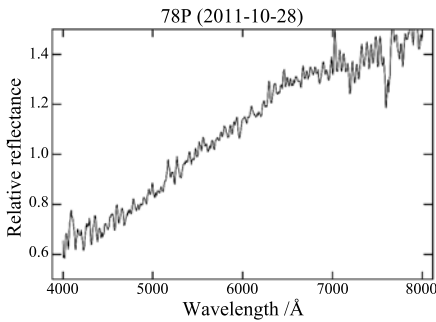Fig. 4 The relative reflectance spectrum of the comet 49P on 4th Jan. 2012

Fig. 5 The relative reflectance spectrum of the comet 78P on 28th Oct. 2011
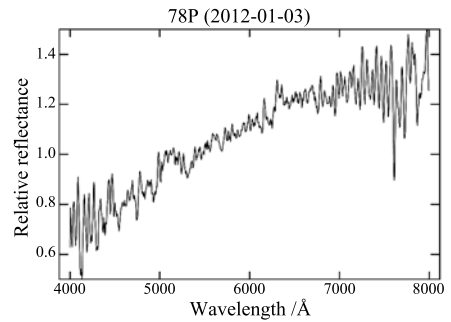

Fig. 6 The relative reflectance spectrum of the comet 78P on 3rd Jan. 2012

spectral distance, we calculate the spectral distances of the spectral data of the every comet relative to the standard spectral data of the 24 asteroid types in the Bus-DeMeo taxonomy, then, according to the distance, to judge that the comets are most close to which types.

On the one-dimensional spectrum of an object, to take n points with fixed intervals (for example 500 Å). Then, we can image an n-dimensional spectral space, the data of the n points can be considered as the coordinates of the comet in this n-dimensional spectral space, correspondingly, the 24 asteroid spectral types of the Bus-DeMeo taxonomy have also the coordinates in this n-dimensional spectral space. Thus, we need only to calculate the spectral distances of the comet relative to the 24 asteroid spectral types of the Bus-DeMeo taxonomy, and to see which distance (or distances) is (are) most short, it indicates that the spectral characteristic of the comet is closer to that type (or those types). In combination with the relative reflectance spectrum of the comet, by further analysis and comparison, the spectral type of the comet can be finally determined.

Therefore, the spectral distance can be defined to be

$$d_x = \sqrt{\sum_{k=1}^{n}(X_k - Y_k)^2},$$

in which d_k is the spectral distance between the unclassified spectrum X and the classified asteroid spectrum Y by the Bus-DeMeo taxonomy, k indicates a coordinate in the spectral space, n represents the total number of the coordinates in the spectral space (or the number of dimensions of the spectral space).
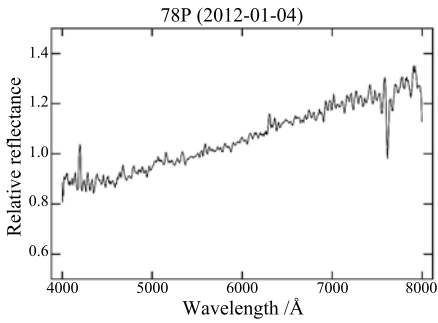

Fig. 7   The relative reflectance spectrum of the comet 78P on 4th Jan. 2012
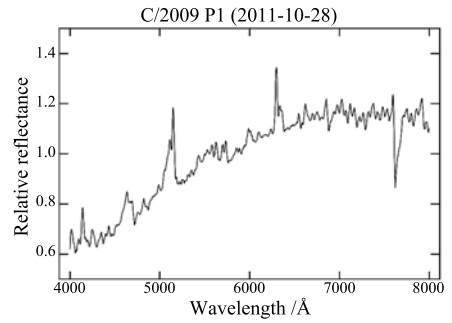

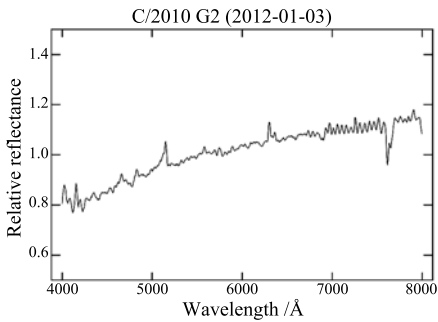Fig. 8 The relative reflectance spectrum of the comet C/2009 P1 on 28th Oct. 2011

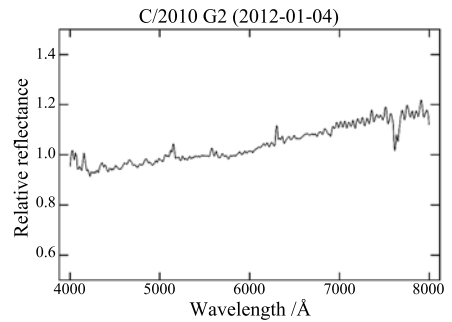Fig. 9 The relative reflectance spectrum of the comet C/2010 G2 on 3rd Jan. 2012

Fig. 10 The relative reflectance spectrum of the comet C/2010 G2 on 4th Jan. 2012

The magnitude of the spectral distance indicates the similarity of the unknown type of cometary spectrum with the different asteroid spectral type, the smaller the distance, the closer the two spectral types.

The standard data of the 24 asteroid spectral types of the Bus-DeMeo taxonomy cover the wavelength range 4500∼24500 Å, this is a broad waveband from visible light to infrared. But our observational equipment can obtain only the information at the visible light waveband, the wavelength range of good response is 4000∼8000 Å. So, we can make comparison only in the common part of the two ranges, namely using the data of 4500∼8000 Å.

The data of the Bus-DeMeo taxonomy are uniformly distributed with an interval of 500 Å, so there are 8 data points in the 4500∼8000 Å range. Hence, we adopt the 3-order spline function to make the data smoothing on the cometary spectrum, and take as well one point for the every 500 Å in the range of 4500∼8000 Å. Thus, 8 points are taken for each

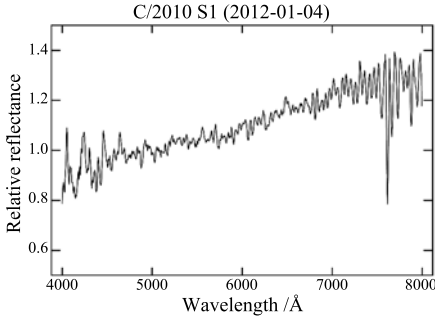comet. In other words, in this paper the total number of the coordinates of the spectral space is $n = 8$.

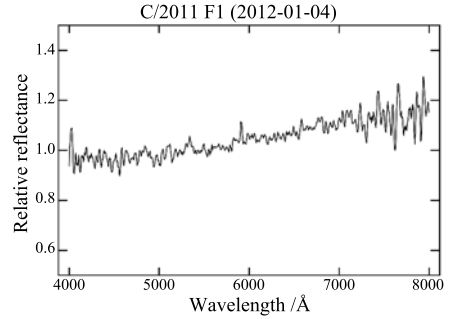Fig. 11　The relative reflectance spectrum of the comet C/2010 S1 on 4rd Jan. 2012

Fig. 12　The relative reflectance spectrum of the comet C/2011 F1 on 4rd Jan. 2012

Table 2 shows the data of the six comets in the 10 observations, the distances relative to the 24 asteroid spectral types of the Bus-DeMeo taxonomy have been arranged according to the sequence from near to remote, and only the four nearest types remain. In this table, "Type" means the spectral type, "Distance" indicates the spectral distance, and the number in the brackets under the comet name indicates the observational time.

Table 2　The spectral distances of cometary spectra relative to the 24 asteroid spectral types of the Bus-DeMeo taxonomy

	Type	Distance		Type	Distance		Type	Distance
	O	0.314627875		A	0.756530237		A	0.213739327
49P	B	0.350706573	49P	Sv	0.774872248	78P	Sv	0.359467801
(2012-01-03)	C	0.360062633	(2012-01-04)	L	0.801371325	(2011-10-28)	L	0.379882745
	Cb	0.365908595		D	0.830187931		Sa	0.384849971
	A	0.137193768		Sv	0.061434925		Sa	0.124541198
78P	Sv	0.15364677	78P	L	0.062857378	C/2009 P1	Sr	0.142960519
(2012-01-03)	L	0.162292729	(2012-01-04)	S	0.08173402	(2011-10-28)	R	0.14595996
	S	0.191130139		D	0.088322421		V	0.150399169
	K	0.048046228		T	0.055183784		Sv	0.14334162
C/2010 G2	Xe	0.066916665	C/2010 G2	D	0.082378699	C/2010 S1	L	0.161064645
(2012-01-03)	T	0.078239632	(2012-01-04)	Xe	0.08757197	(2012-01-04)	S	0.184023966
	Sq	0.084614656		K	0.091945908		D	0.193655932
	Xe	0.077043429						
C/2011 F1	K	0.092012445						
(2012-01-04)	T	0.101496256						
	Xk	0.119178396						

5. ANALYSIS AND CONCLUSIONS

The 24 asteroid spectral types of the Bus-DeMeo taxonomy given at the SMASS website are shown in Fig.13[1].

According to the averaged data of the 24 asteroid spectral types of the Bus-DeMeo taxonomy given at the SMASS website, we take the corresponding data in the wavelength

range of 4500∼8000 Å, and plot the relative reflectance spectra of the 24 spectral types, as shown in Figs.14∼17.

From Figs.14∼16, we can find that in the range of 4500∼8000 Å, the spectrum profiles in the same group of spectral types generally differ rather small, especially for the several sub-types of the S-complex and X-complex, this makes our determination become difficult, hence, besides the spectral distance, we have to combine with the K-S test of the data in order to make the analysis.
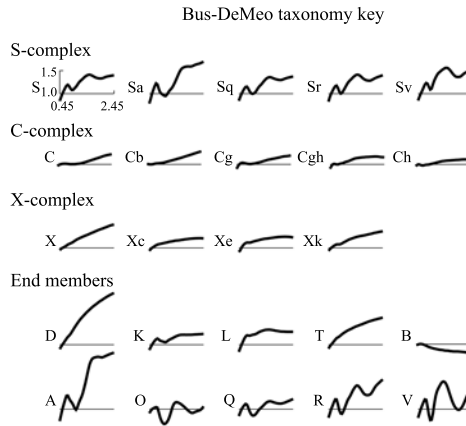

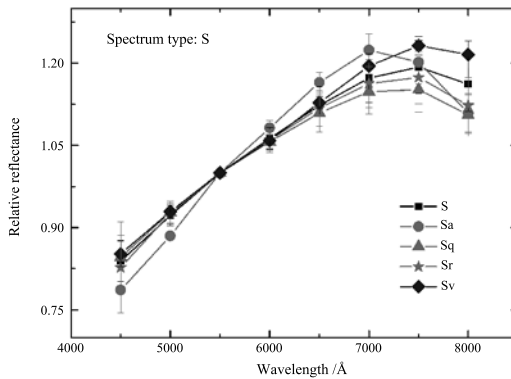Fig. 13 The 24 asteroid spectral types of the Bus-DeMeo taxonomy[1]

Fig. 14 The S-complex of the Bus-DeMeo taxonomy, including the S, Sa, Sq, Sr, and Sv types

In addition, the atmospheric condition during the observations should be taken into consideration. In the night of 3rd January, the seeing was as bad as 4.5″, and the slit width of our spectrograph was 3″, less than the value of atmospheric seeing, hence the data on 3rd Jan. are worse, at a low confidence level. But the seeing at the night of 4th Jan. was fairly good, it was 2.5″, less than the slit width, so the data at the night of 4th Jan. have a high confidence level. The following analysis will mainly rely on the data at the night of
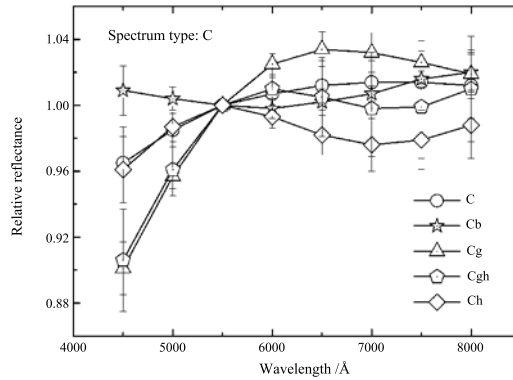
4th Jan.

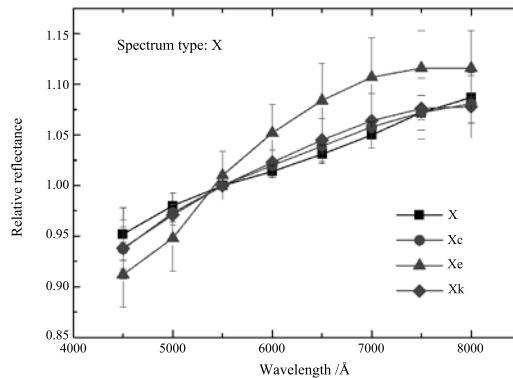Fig. 15   The C-complex of the Bus-DeMeo taxonomy, including the C, Cb, Cg, Cgh and Ch types

Fig. 16   The X-complex of the Bus-DeMeo taxonomy, including the X, Xc, Xe and Xk types

5.1 About the Comet 49P

The observations were made on 3rd and 4th January 2012, respectively. Because of the rather low brightness during the observations, the obtained data have a rather low signal to noise ratio (Figs.3,4), leading to rather large errors in the succeeding analysis, which demonstrate themselves as

(1) The sequences of spectral distance derived respectively from the spectral data of 3rd Jan. and of 4th Jan. differ with each other significantly;

(2) The respective spectral distances derived from the data of 3rd Jan. and of 4th Jan. tend to be large, being obviously greater than 0.1, especially on 4th Jan., the smallest spectral distance even approached to 1.

(3) After the spectral distances derived from the data of same date are arranged in order, the differences between the several nearest spectral distances are very small, within tolerance limits. The smallest spectral distance has no significant superiority over the neighboring ones.

We have tried to average the data of the two days, but the signal to noise ratio is still bad, and the spectral distances calculated by the averaged data are still very large.

Hence, according to the existing data, we cannot classify 49P into any one of asteroid types.

5.2 About the Comet 78P

The observations were made on 28th Oct. 2011, 3rd and 4th Jan. 2012, respectively, totally three sets of data were obtained. Comparing the three sets of data, we can find that for the sequences of spectral distance derived respectively from the data of 28th Oct. 2011 and of 3rd Jan. 2012, the former three types are completely consistent: the A-type corresponds to the smallest spectral distance, the next ones are the Sv-type and L-type. But the data of 4th Jan. 2012 show that the Sv-type corresponds to the smallest spectral distance, the next ones are the L-type and S-type. Considering that the weather during the observation of 4th Jan. is best, and the signal to noise ratio is highest, so the data of this date are more reliable for the analysis. The data of 4th Jan. indicate that the smallest spectral distance corresponds to the Sv-type, and the data of other two observations show that the spectral distance of the Sv type is secondly small, and not very different from the smallest one, so it is believable that the spectral type of the comet 78P is close to the Sv-type.

Then, we investigate further the relative reflectance spectra of the comet (Figs.5∼7), it is found that the spectral profiles tend obviously to rise, averagely, the relative reflectance at 4500 Å is about 0.8, and the maximum value is a little greater than 1.2. Comparing with the spectral profiles corresponding to the A-type (Fig.17), Sv-type (Fig,14), and L-type (Fig.17) of the Bus-DeMeo taxonomy, in the same wavelength range (4500∼8000 Å), for the L-type the maximum relative reflectance can approach to 1.2, it is approachable as well for the Sv-type and A-type, and they have similar profiles. Considering that the data of 4th Jan. are better, we focus our attention to the relative reflectance spectrum of 4th Jan. (Fig.7), this spectrum has a lowest intensity of about 0.8, and a peak value at about 7500 Å, but the lowest intensity of the A-type is less than 0.75, and the peak value appears at 7000 Å, only the Sv type, which has the lowest intensity of about 0.8 and attends the peak intensity at ∼7500 Å, is consistent best with the spectral profile of 4th January.

Then again, we inspect the result of K-S test. The calculating method of the K-S test is: adopting the method of sliding average to filter the raw observational data, the filter factor adopts unitedly 0.5, then the K-S test is made on the filtered data and the 24 Bus-DeMeo spectra, the significance is 0.05. As the result of K-S test, H indicates the similarity between the two distributions, if $H = 0$, then the spectrum of the observed source and the spectral type in the Bus-DeMeo taxonomy have similar distributions at this waveband; if $H = 1$, then the spectrum of the observed source and the spectral type in the Bus-DeMeo taxonomy have no similar distributions. P represents the probability of erroneous judgment, the smaller the value of P, the higher the probability of correct judgment.

Table 3 gives the results of K-S tests of the three sets of observed data of the comet 78P with respect to the A-type, Sv-type, and L-type of the Bus-DeMeo taxonomy. It is found that the results of K-S tests support also the spectral type of 78P being classified as the Sv-type. For the three sets of observational data, the values of H corresponding to the Sv-type are all zero. For the high-quality data of 4th Jan., we have: $H = 0$, $P = 0.9652$,
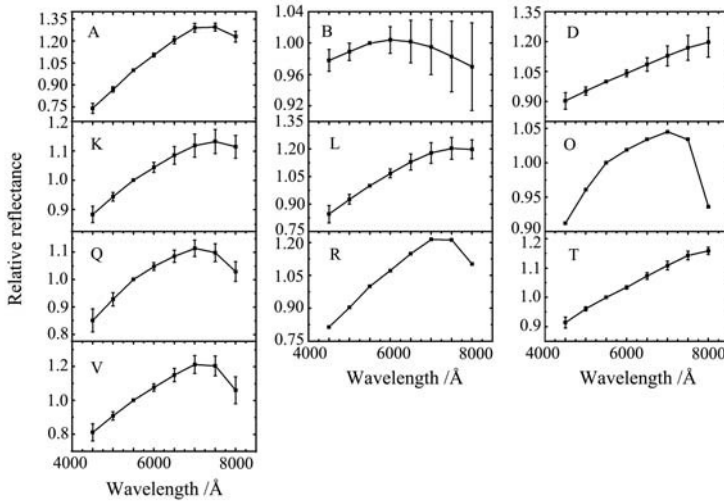
Fig. 17   A, B, D, K, L, O, Q, R, T, and V types of Bus-DeMeo taxonomy

although the value of P is rather high, but anyhow $H \neq 1$, in support of this judgment.

Finally, synthesizing the different factors, we believe that the spectral type of the comet 78P approximates to the Sv-type.

Table 3   The K-S test results between the three sets of observational data of 78P and the A-type, Sv-type, and L-type

2011-10-28			2012-01-03			2012-01-04		
Type	H	P	Type	H	P	Type	H	P
L	0	0.0696	L	0	0.1784	A	0	0.3226
Sv	0	0.1094	Sv	0	0.352	L	0	0.9256
A	0	0.3068	A	0	0.8602	Sv	0	0.9652

5.3 About the Comet C/2009 P1

The observation was made on 28th Oct. 2011. Because of the high brightness of the comet, the image has a good signal to noise ratio. According to the sequence of the calculated spectral distances, the former three places are the Sa-type, Sr-type, and R-type.

Then, to investigate the relative reflectance spectrum of the comet (Fig.8), it is found that the spectrum rises apparently at the wavelengths less than 7000 Å, and tends to be flat at the wavelength around 7000 Å, then it declines slightly, at the peak the relative reflectance is about 1.1. In comparison with the spectral profiles corresponding to the Sa-type, Sr-type (both in Fig.14), and R-type (Fig.17) of the Bus-DeMeo taxonomy, in the same wavelength range (4500∼8000 Å), the peak values of relative reflectance of the Sa-type and R-type are all greater than 1.2, and the final declines are rather steep, only the peak relative reflectance of the Sr-type is about 1.1, and the final decline is rather gentle.

Then again, to examine the K-S test result (Table 4), the values of H are all zero, indicating that the spectral data of C/2009 P1 and the three types have similar distributions. But the P-value corresponding to the Sr-type is quite large, the probability of erroneous

judgment is relatively large.

Table 4 The K-S test results between the observational data of C/2009 P1 and the Sa-type, R-type and Sr-type

	2011-10-28	
Type	H	P
Sa	0	0.1662
R	0	0.1662
Sr	0	0.6382

According to the sequence of spectral distances, C/2009 P1 is most close to the Sa-type; according to the analysis of spectral profile, C/2009 P1 is most close to the Sr-type; and according to the K-S test result, it is most close to the Sa-type and R-type. Synthetically, at least the spectral type of the comet C/2009 P1 is most close to the S-complex, whether the Sa-type or the Sr-type in the S-complex, it needs more observational data to make decision.

5.4 About the Comet C/2010 G2

The observations were made respectively on 3rd and 4th Jan. 2012, the sequences of spectral distance obtained from the data of the two days are different: on 3rd Jan., the K-type is arranged at the first place, then are arranged the Xe-type, and T-type; on 4th Jan., the T-type is arranged at the first place, then are arranged the D-type, Xe-type, and K-type. Considering that the data quality on 4th Jan. is better, we focus our attention to the T-type.

We have tried to make average on the data of two days, to calculate the spectral distances and arrange them in order again, the obtained four smallest spectral distances correspond to, in order, the T-type, K-type, Xe-type, and D-type.

To inspect the relative reflectance spectra of the comet (Figs.9∼10), it is found that the spectra rise gently and almost linearly, and have only small fluctuations, the relative reflectance is about 0.9 at 4500 Å, about 1.15 at 8000 Å, and the spectrum in Fig.10 sinks markedly at 6000 Å. Comparing with the spectral profiles corresponding to the K-type, T-type, D-type (Fig.17), and Xe-type (Fig.16) of the Bus-DeMeo taxonomy, in the same wavelength range (4500∼8000 Å), the Xe-type spectrum profile rises in "S" shape, the K-type spectrum profile has an apparent decline in the end, and does not sink at 6000 Å, all differs from the observed spectra. The T-type and D-type have analogous spectrum profiles, judging from the points of the attained peak intensity and the depression at 6000 Å, the T-type seems to be more suitable.

To look at the K-S test result again (Table 5), all the values of H are zero, indicating that at this waveband, the spectral data of C/2010 G2 and the D-type, T-type have similar distributions. But the P-value corresponding to the T-type is relatively large, especially for the data of 4th Jan., the value of P is as high as 0.9854, indicating that the probability of erroneous judgment is very large.

Table 5 The K-S test results between the two sets of observational data of C/2010 G2 and the D-type, T-type

2012-01-03			2012-01-04		
Type	H	P	Type	H	P
D	0	0.2314	D	0	0.7029
T	0	0.638	T	0	0.9854

Therefore, according to the sequence of the averaged spectral distances, C/2010 G2 is most close to the T-type; according to the analysis of spectral profiles, C/2010 G2 is still most close to the T-type. According to the K-S test results, C/2010 G2 and T-type have similar distributions, although the probability of erroneous judgment is rather large, but at least H is not equal to 1. Synthetically, we suggest finally that the spectral type of the comet C/2010 G2 approximates to the T-type.

5.5 About the Comet C/2010 S1

The observation was made on 4th Jan. 2012. According to the sequence of the calculated spectral distances, the former three are the Sv-type, L-type, and S-type, and the spectral distance corresponding to the Sv-type has an obvious superiority over others.

To inspect the relative reflectance spectrum (Fig.11), it is found that the spectrum rises gently, and is lacking in characteristics, there seems to be a depression at about 6000 Å, the peak relative reflectance exceeds slightly 1.2, and there is no apparent decline in the end. To compare with the spectrum profiles of the Sv-type (Fig.14), L-type (Fig.17), and S-type (Fig.14) of the Bus-DeMeo taxonomy, at the same wavelength range, these profiles are all similar with each other, but the peak of the S-type profile cannot attain 1.2, the peak of the L-type profile approximates 1.2, only the peak of the Sv-type profile exceeds a little 1.2, so Sv-type satisfies most the intensity characteristic of the cometary spectrum. The K-S test results (Table 6) of $H = 0$ indicate that the spectral data of C/2010 S1 and the three spectral types have similar distributions. But the value of P corresponding to the Sv-type is rather large, indicating that the probability of erroneous judgment is large.

Table 6 The K-S test results of the observational data of C/2010 S1 with respect to the S-type, L-type and Sv-type

Type	2012-01-04	
	H	P
S	0	0.4154
L	0	0.5447
Sv	0	0.9112

Hence, according to the sequence of the calculated spectral distances, C/2010 S1 is most close to the Sv-type; according to the analysis of spectrum profiles, C/2010 S1 is also most close to the Sv-type. According to the K-S test results, C/2010 S1 and the Sv-type have similar distributions, although the probability of erroneous judgment is rather large, but at least H is not equal to 1. Synthetically, we suggest finally that the spectral type of the comet C/2010 S1 approximates to the Sv-type.

5.6 About the Comet C/2011 F1

The observation was made on 4th Jan. 2012. According to the sequence of the calculated spectral distances, the former three are the Xe-type, K-type, and T-type.

From the relative reflectance spectrum of the comet, we can find that the spectrum rises gently, there is a marked depression at about 6000 Å, the relative reflectance at the profile's peak is about 1.1, and that it has no trend to decline in the end, these characteristics are very like those of the comet C/2010 G2 mentioned above. To compare with the spectral profiles corresponding to the Xe-type (Fig.16), K-type, and T-type (Fig.17) of the Bus-DeMeo taxonomy, in the same wavelength range (4500∼8000 Å), the Xe-type spectrum profile exhibits an S-shaped rise, the K-type has a significant decline in the end, and has a

depression at 6000 Å, these are inconsistent with the observed spectrum, only the T-type is rather consistent.

The K-S test results (Table 7) of $H = 0$ indicate that the spectral data of C/2011 F1 and the T-type, Xe-type have similar distributions in this waveband. But their values of P are rather high, indicating that the probability of erroneous judgment is rather large.

Table 7   The K-S test results between the observational data of C/2011 F1 and T-type, and Xe-type

	2012-01-04	
Type	H	P
T	0	0.638
Xe	0	0.638

Hence, according to the sequence of the spectral distances, C/2011 F1 is most close to the Xe-type; according to the analysis of spectrum profiles, C/2010 S1 is most close to the T-type. According to the K-S test results, C/2010 F1 and the two spectral types have similar distributions, although the probability of erroneous judgment is rather large, but at least H is not equal to 1. Synthetically, we suggest finally that the spectral type of the comet C/2011 F1 approximates to the T-type.

6. SUMMARY AND DISCUSSION

We have observed the spectra of six comets, and according to the concept of spectral distance to judge the similarity of the spectra of the six comets with the existing asteroid spectral types of the Bus-DeMeo taxonomy. The obtained conclusions are as follows: the spectral type of the comet 78P approximates to the Sv-type, the spectral type of the comet C/2009 P1 approximates to the Sa-type or Sr-type in the S-complex, the spectral type of the comet C/2010 G2 approximates to the T-type, the spectral type of the comet C/2010 S1 approximates to the Sv-type, and the spectral type of the comet C/2011 F1 approximates to the T-type. Because the data of the comet 78P have a bad signal to noise ratio, we cannot obtain a definite conclusion. For these comets, we may boldly infer that they probably have a certain evolutionary relation with that asteroids of corresponding spectral types, including the similarity of moving orbits. Later, we may calculate the orbits of some comets, as well as the orbits of some representative asteroids of corresponding spectral types, then to search for the correlation between their orbits, perhaps some thing new might be discovered.

Our result indicates that to determine the similarity of spectra by spectral distances, then to verify it by the K-S tests, it is a feasible method. This point is very important, which makes possibly to classify the cometary spectra by using this method in near future.

The greatest shortage of our work is that the wavelength range of our observed spectra is not wide enough. The 24 asteroid spectral types of the Bus-DeMeo taxonomy require the wavelength range from visible light to infrared (4500∼24500 Å), of which our data can cover only a part (4500∼8000 Å). This part exhibits less spectral characteristics, and the number of points taken for calculating spectral distances is also small, the calculated results will have rather large errors, and it is difficult to make a precise judgment by though spectral characteristics, because many important characteristics for the judgment are concentrated at 10 000 Å, even at 20 000 Å.

For the future work, as mentioned above, now the wavelength range of our spectral observation is not wide enough, later in the similar work, we will take simultaneously the infrared spectra of target objects as far as possible for the more accurate analysis. More importantly, we may obtain the spectra of more comets using the existing spectroscopic equipment. As soon as the sample is large enough (for example, over 30 comets each of which is observed for two and more times), we can make the classification on the cometary spectra according to their spectral distances. Of course, not only the continuum spectra, we have to consider their differences in atomic and molecular lines, if possible we will make observations with high-resolution grating to obtain the spectral details. This work is somewhat initiative, because so far there is not yet a very good taxonomy of cometary spectra. Thus, the requirement of broad wavelength range of the Bus-DeMeo taxonomy can be avoided and it is difficult to obtain the infrared spectra of comets with present domestic instruments. Meanwhile, it is also in favor of the analysis of the fine features of cometary spectra in the wavelength range of 4000∼8000 Å. In addition, by the multiple times of observations of a comet in a long duration, we can analyze as well the possible variations of spectrum profile with its position relative to the sun and the angle with respect to us.

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