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Dynamical and physical properties of comet–asteroid transition objects*

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Abstract. In the last few years it has been pointed out that, from both physical and dynamical point of view, it is becoming more and more difficult to distinguish comets from asteroids and indeed there are some examples of small bodies first designated as comets which had, later, to be reclassified as asteroids and vice versa (Hartmann et al., 1990; McFadden, 1994). In order to investigate the evolutionary path of comets and asteroids in terms of both dynamical and physical properties, we performed spectroscopic observations of three objects discovered between 1990 and 1995 – (6042) *1990 WW*$_2$, (6144) *1994 EQ*$_3$, and *1995 QY*$_2$ – and analyzed their orbital evolution. Obtained spectra show the typical trend of low-albedo, "primitive" objects, similar to those of outer-belt asteroids and comet nuclei. The dynamical analysis shows that (6042) *1990 WW*$_2$ is on a stable orbit with a typical asteroidal behavior; (6144) *1994 EQ*$_3$ is on a Jupiter-crossing chaotic orbit and in the past could have spent some time in a Jupiter's *horsehoe* orbit; *1995 QY*$_2$ is a Mars crosser and librates about the 15/7 resonance with Jupiter and has a 40% chance to make a transition from asteroid to comet orbit over a timescale of about 3–5$\times 10^5$ yr.

Key words: asteroids – comets

1. Introduction

In the last years theoretical studies and observational results have pointed out the presence of a class of objects that could represent a transitional state between asteroids and comets. Most of these bodies are classified as asteroids, but they can show some cometary characteristics: possible outgassing activity, cometary-type orbits, meteor-shower association, and taxonomic type consistent with a carbon-rich/primitive composition (i.e. low albedo).

From the dynamical point of view, a class of transition objects between comets and asteroids has been identified: such bodies, called "cometary asteroids", have asteroidal appearance and exhibit dynamical characteristics typical of Jupiter-family short-period comets (Harris and Bailey, 1996). Moreover, Marzari et al. (1995) have suggested that a few tens of the currently observed short-period comets may have originated in the Trojan clouds. They showed that typical family-forming Trojan collisions eject a significant percentage of the resulting fragments into unstable orbits: such unstable Trojan fragments experience close encounters with Jupiter, becoming indistinguishable from *i)* Jupiter-family comets, *ii)* comets undergoing temporary captures by Jupiter, *iii)* objects with Jupiter-crossing or -approaching orbits. The activity timescale of a periodic comet, computed on the basis of the mean-rate decrease of the luminosity in a century, can be about $1-3\cdot 10^3$ yr (150–500 revolutions; Kresák and Kresáková, 1990). The final stage of the evolution of such objects is not yet well known: the discoveries of a possible faint cometary activity in the Apollo asteroids (1566) *Icarus* and (2201) *Oljato* (McFadden, 1994), and the coincidence between asteroid (4015) *1979 VA* and comet Wilson-Harrington (1949 III) (Bowell, 1992) could be the first verifications of the hypothesized phenomenon of dormant comets, showing the existence of residual sporadic cometary activity.

Among the possible asteroid-comet transition objects, the dark asteroids, classified as C, P and D type (Barucci et al., 1987; Tholen 1984; Tedesco et al., 1989) seem to play a fundamental role. In the last few years, spectroscopic and photometric observations together with theoretical analyses have led to the conclusion that outer-belt asteroids, and in particular the reddest ones (D-class objects), which dominate the Trojan region and are thought to have preserved part of their original composition,

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* Based on observations carried out at the European Southern Observatory (ESO), La Silla, Chile.

Table 1. Dynamical evolution over a time span of 821.4 years of (6042) *1990 WW*$_2$: (top) orbital parameters at the starting point of the integration (first line) and every 50 000 days, from JD 2 300 000.5 to JD 2 600 000.5; (middle) close encounters with planets; (bottom) possible librations about mean motion resonances with the giant planets.

6042 1990 WW2

Orbital parameters

Epoch	T	a	e	ω	Ω	i	L	B
1996 1 18	1995 4 1.1	3.05257	0.45193	286.241	88.913	15.858	15.761	−15.210
1585 2 1	1584 7 11.3	3.04108	0.45826	259.457	112.893	15.628	11.955	−15.358
1721 12 25	1723 3 13.4	3.06056	0.45257	269.483	104.024	15.413	13.488	−15.412
1858 11 17	1856 6 21.5	3.04286	0.45892	276.305	97.547	15.505	14.088	−15.409
1995 10 10	1995 4 1.1	3.05256	0.45190	286.245	88.913	15.858	15.765	−15.210
2132 9 1	2133 11 5.3	3.05352	0.44790	292.270	83.147	16.259	16.249	−15.017
2269 7 25	2267 4 24.1	3.04485	0.44403	300.865	75.985	16.985	17.988	−14.522
2406 6 17	2406 1 7.3	3.06359	0.42895	306.242	71.261	17.542	18.812	−14.069

Close encounters (Outer planets: $d < 0.50 AU$, Inner planets: $d < 0.05 AU$)

None within the given distances

Possible librations about the following resonances

None within the given time span

IAU designation: 1990 WW2 Number of revolutions in the integration interval: 154
Reference orbit: Bowell

show spectral and mineralogical characteristics very similar to those of cometary nuclei (Hartmann et al., 1987; Jewitt and Luu, 1990). As proposed by Jones et al. (1990), accretion of ice and anhydrous silicates from the solar nebula, combined with relic interstellar organic kerogen, formed very dark, volatile-rich asteroids, of which low-albedo asteroids, especially D-type, may be representative. If dark and distant asteroids could be exhausted comet nuclei, some of the low-albedo asteroids may still contain water ice and organic compounds.

Information about these objects is very poor: the aim of our work is to improve the data set of these bodies and to investigate their physical and dynamical properties, in order to sort out a possible link between asteroids and comets, and explore the possible mechanisms responsible for comet-asteroid transitions. Here we present:

- analysis of the dynamical evolution of three objects [(6042) *1990 WW*$_2$, (6144) *1994 EQ*$_3$, *1995 QY*$_2$], classified as asteroids and having "unusual" orbits;
- spectroscopic observations of these objects to achieve information about their mineralogy.

2. Dynamical analysis

The three observed objects have been integrated a first time with the same code used to build the First General Page of the *Atlas of Dynamical Evolution of Short-Period Comets* (Carusi et al., 1995). Initial orbital parameters of these objects have been derived from the Bowell (1996) catalogue of asteroid orbital data. The integration of the orbits, over a time interval of 821.4 years centered on 1996 (1585–2406), has been performed using the Everhart's routine RADAU to the 15^{th} order (Everhart, 1985), taking into account the gravitational influence of the Sun and all planets. All passages of minor bodies within a sphere of a given radius d around each planet have been recorded as described in Carusi and Dotto (1996) and in Carusi et al. (1985a,b).

Tables 1, 2 and 3 summarize, for each object, the results obtained by the Atlas orbital integration. These Tables contain: *i)* the listing of the orbital parameters at the starting point of the integration (first line) and every 50 000 days, from JD 2 300 000.5 to JD 2 600 000.5. The $Epoch$ and the time of perihelion passage T are given, according to the Gregorian Calendar, in year, month and day. The other columns report the semi-major axis of the orbit a (in AU), its eccentricity e, the argument of perihelion ω, the longitude of the ascending node Ω, the inclination i and the longitude and latitude of the perihelion (L and B). All angular elements are in degrees and their fractions, and are referred to the mean equinox and ecliptic of 2 000.0; *ii)* the epochs and the minimum distances of all encounters within a distance d from the planets; *iii)* all possible librations about mean motion resonances with the giant planets, detected by an automatic procedure among a list of 53 possible mean-motion resonances.

Figs. 1, 2 and 3 show, for each object, the obtained evolution of dynamical parameters, as in the Second General Page of the *Atlas of Dynamical Evolution of Short-Period Comets* (Carusi et al., 1995). Plots have the time in abscissa from 1 500 to 2 500 AD and represent: *i)* the energy diagram, since the ordinate $-1/a$ is proportional to the orbital energy. A vertical arrow on the abscissa, close to the year 2 000, indicates the epoch 1.0 January 1993. On the right side some of the 53 resonance levels with Jupiter, taken into account in the search for librations, are indicated; *ii)* the diagram of the latitude and longitude of the perihelion (B and L); *iii)* the diagram of the Tisserand parameter (T) with respect to Jupiter; *iv)* the inclination i and the aphelion and perihelion distances diagrams (Q and q, respectively).

(6042) *1990 WW*$_2$ has an high inclination orbit, which seems to have a typical asteroidal behavior with very small variations of the semi-major axis and of the aphelion and perihelion distances; (6144) *1994 EQ*$_3$ is on a Jupiter-crossing orbit and, as a consequence, the semimajor axis varies chaotically due to repeated close encounters with Jupiter, while *1995 QY*$_2$ is a Mars crosser and librates about the 15/7 resonance with Jupiter.

To investigate in more detail the dynamical evolution of the last two objects [(6144) *1994 EQ*$_3$ and *1995 QY*$_2$], we have integrated for a long-time span a sample of 15 "clone" orbits for each object. The clones were obtained by changing the last digit of the current orbital elements. The orbital integration, performed with the Everhart's routine RADAU, includes all planets.

The clones of (6144) *1994 EQ*$_3$ have been integrated backwards for 1×10^5 yr to look for a possible connection with the Edgeworth-Kuiper Belt or with the Trojan swarms (as it will be shown below, the asteroid very probably belongs to the D-class). 3 over 15 of the analyzed clones were temporarily trapped for short intervals of time, of the order of 10 000 yr, in the 1/1 resonance with Jupiter on *horseshoe* orbits and one was trapped on a more stable orbit for more than 20 000 yr. Due to the high degree of chaos of the orbit, it is not possible to discriminate between the two sources only from a dynamical point of view. However, the orbital integrations show that this object could have spent in the past some time in a Jupiter's *horseshoe* orbit,

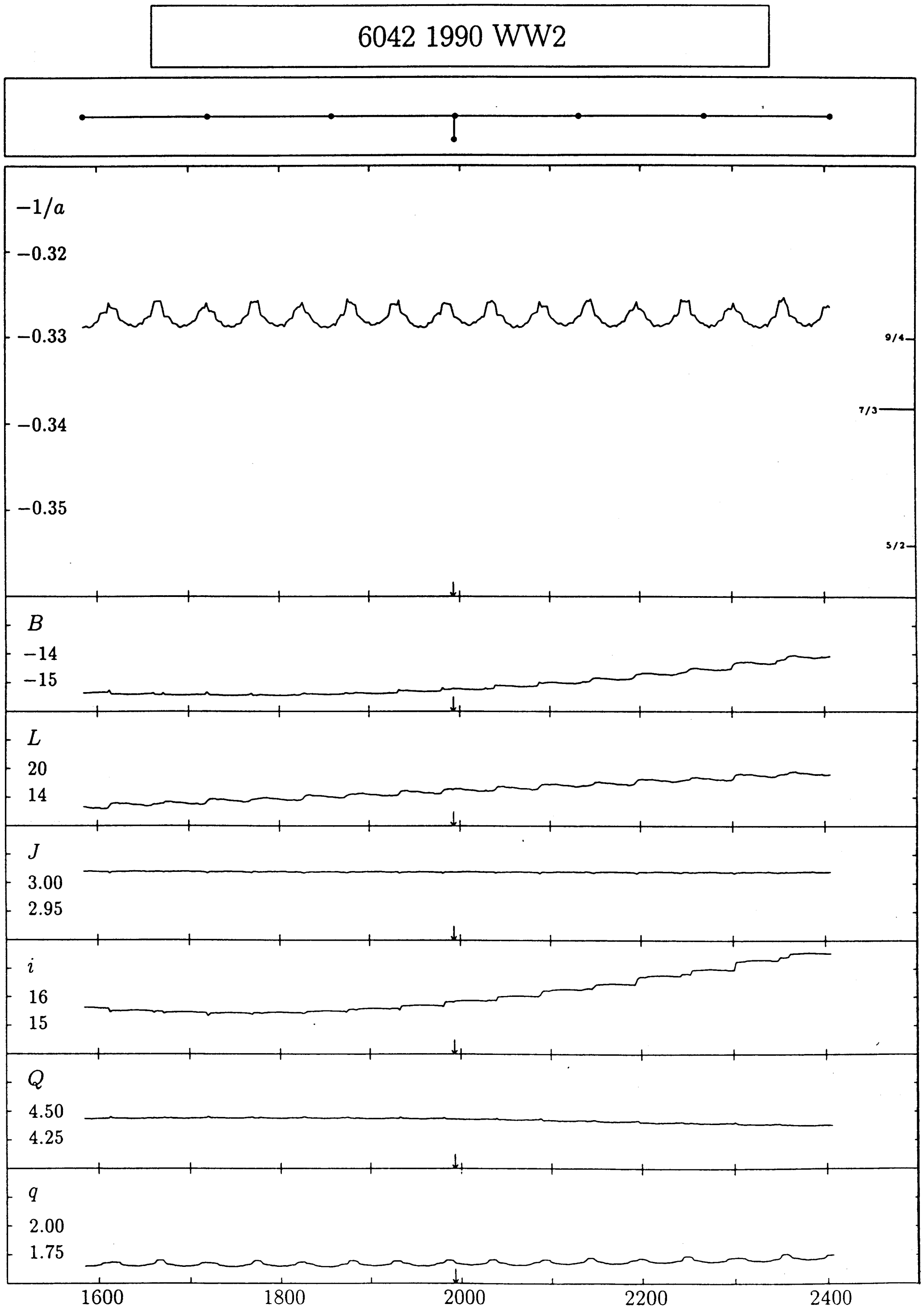

Fig. 1. Evolution of dynamical parameters of (6042) *1990 WW*$_2$. For the description see the text.

as a significant percentage of fragments, generated in a family forming event occurred in the Trojan clouds, does.

The 15 clones of *1995 QY*$_2$ have been integrated forwards in time for 1.2×10^6 yr. 9 over 15 of the clones show a moderate chaotic behavior and jump on different Jovian mean-motion resonances (15:7, 9:4, 11:5), while Mars crossers; some of them become also Earth crossers before the end of the integration. The growth of the eccentricity causes 6 of the clones to become Jupiter crossers, behaving like Jupiter-family comets and being ejected from the Solar System over timescale of the order of 10^5 yr. From a dynamical point of view, we conclude that 1995 QY_2, classified at present as an asteroid, has a 40% chance to make a transition from asteroidal to cometary orbit over a timescale of about $3–5 \times 10^5$ yr.

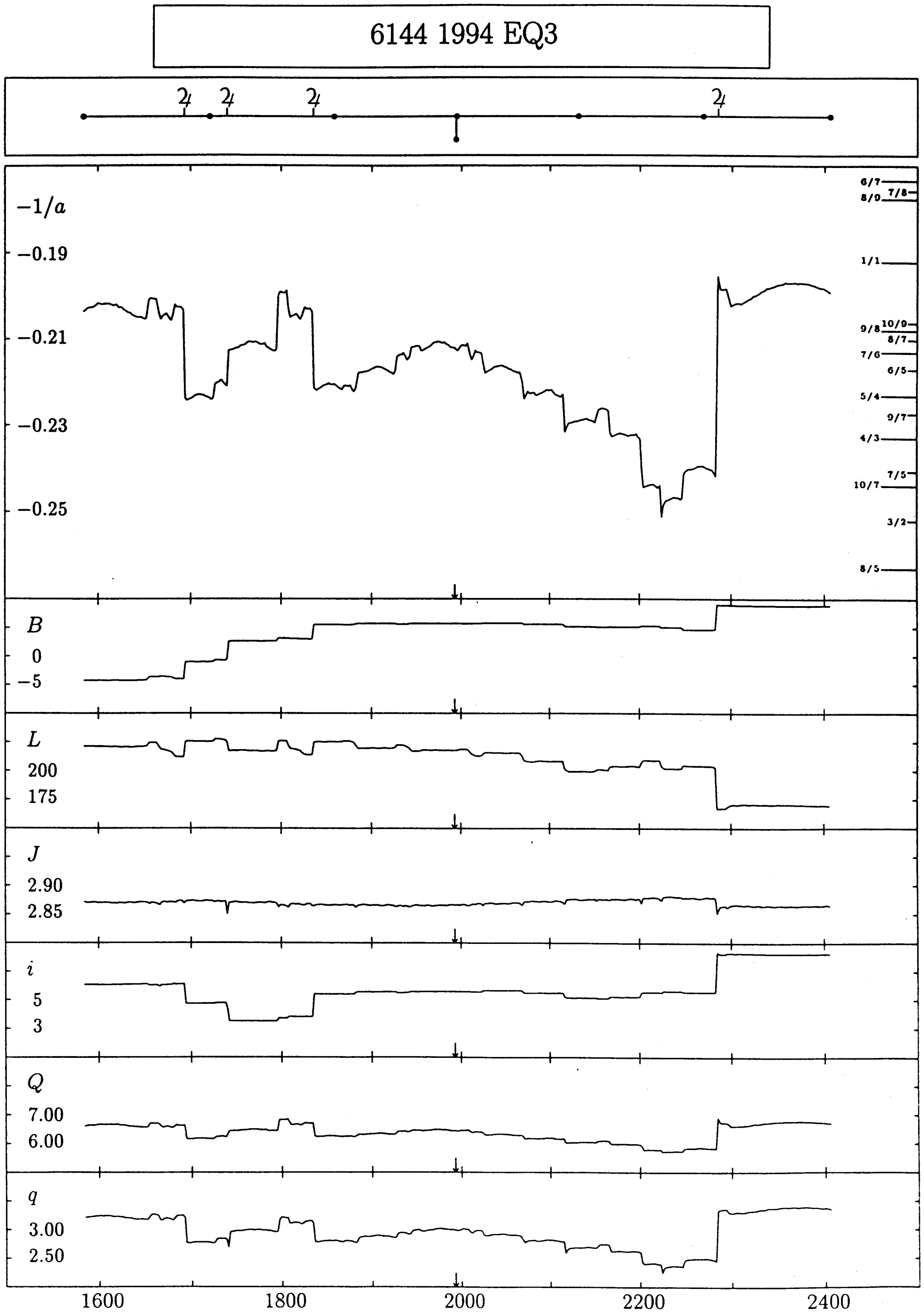

Fig. 2. Evolution of dynamical parameters of (6144) *1994 EQ*$_3$. For the description see the text.

3. Spectral analysis

The low-resolution spectra of (6042) *1990 WW*$_2$, (6144) *1994 EQ*$_3$ and *1995 QY*$_2$ have been obtained during different observing runs in 1994 and 1995. Observations have been performed at the European Southern Observatory (ESO, La Silla, Chile) using the 1.5 m telescope equipped with a Boller & Chivens spectrograph and a Ford CCD (2048 $\times$ 2048 pixels) as detector. The grating used was a 225 gr/mm with a dispersion of 330 Å/mm in the first order. The CCD has a 15 μm square pixel, yielding a dispersion of 5 Å/pixel in the wavelength direction. The spectral range covered is about $0.5 < \lambda < 1\ \mu$m with an instrumental FWHM of 10 Å.

Spectra reduction has been performed using the standard procedures, described by Luu and Jewitt (1990) and Vilas et al. (1993), which include bias subtraction, flat-field correction,

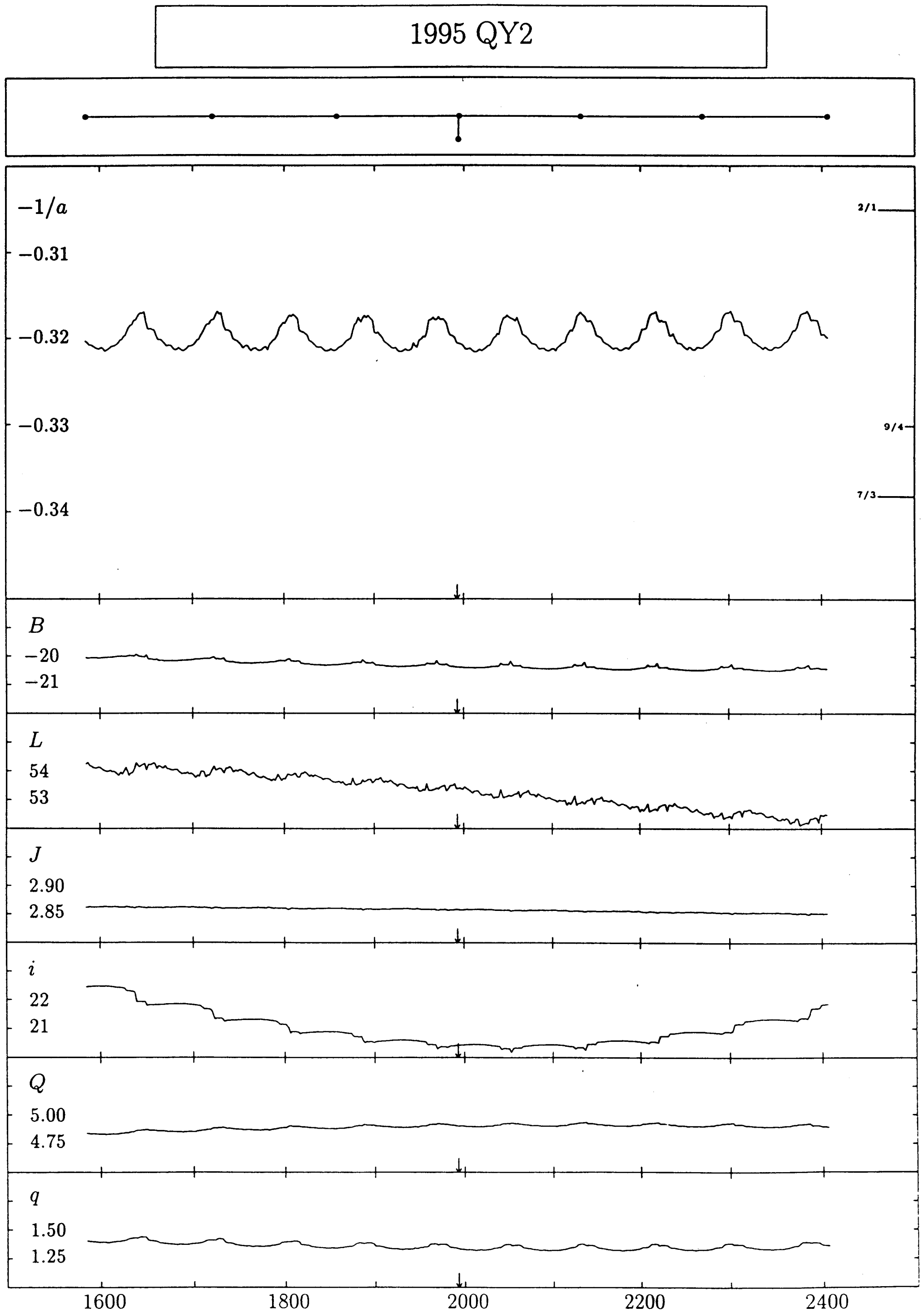

Fig. 3. Evolution of dynamical parameters of *1995 QY*$_2$. For the description see the text.

cosmic-rays removal, wavelength calibration, air mass correction, flux calibration and division by the solar analog star spectrum. Solar analog stars, taken from Hardorp (1978), were observed at airmasses differing less than 0.2 from those of the asteroids. Aspect data of the observed asteroids are reported in Table 4.

Fig. 4 shows the spectra, normalized at 7 000 Å, of (6042) *1990 WW*$_2$, (6144) *1994 EQ*$_3$ and *1995 QY*$_2$, which have been filtered using a weighed-running-box technique. Considering that the red spectral region, starting from about 8 000 Å, is affected by a lower responsivity of the CCD and by the increasing effects of telluric-water absorption and Paschen hydrogen lines, we determined the slope S' of the spectra in the range 5 000–8 000 Å. Taking into account the considerations by Fitzsimmons et al. (1994) and Dahlgren and Lagerkvist (1995) concerning the

Table 2. Dynamical evolution over a time span of 821.4 years of (6144) *1994 EQ_3*: (top) orbital parameters at the starting point of the integration (first line) and every 50 000 days, from JD 2 300 000.5 to JD 2 600 000.5; (middle) close encounters with planets; (bottom) possible librations about mean-motion resonances with the giant planets.

6144 1994 EQ3

Orbital parameters

1996 1 18	1986 9 9.8	4.70225	0.36692	97.629	120.230	5.729	217.896	5.678
Epoch	*T*	*a*	*e*	ω	Ω	*i*	*L*	*B*
1585 2 1	1586 10 9.7	4.91184	0.34584	317.948	263.212	6.336	221.335	−4.239
1721 12 25	1724 1 26.9	4.46561	0.38053	347.492	237.816	4.671	225.348	−1.011
1858 11 17	1857 4 18.8	4.53480	0.38026	95.953	129.330	5.495	225.310	5.466
1995 10 10	1996 11 20.1	4.70310	0.36700	97.613	120.229	5.729	217.880	5.678
2132 9 1	2132 3 25.8	4.36675	0.38471	98.477	100.930	5.195	199.442	5.138
2269 7 25	2271 1 19.9	4.17786	0.40195	125.491	78.769	5.699	204.395	4.638
2406 6 17	2411 12 1.3	5.02066	0.33399	102.471	67.025	9.079	169.649	8.863

Close encounters (Outer planets: $d < 0.50AU$, Inner planets: $d < 0.05AU$)

Planet	*Epoch*	*Distance*	*Planet*	*Epoch*	*Distance*	*Planet*	*Epoch*	*Distance*
Jupiter	1693 4 18	0.3348	*Jupiter*	1740 10 15	0.2628	*Jupiter*	1835 9 16	0.3378
Jupiter	2285 6 18	0.1392						

Possible librations about the following resonances

None within the given time span

IAU designation: 1994 EQ3 Number of revolutions in the integration interval: 82
Reference orbit: Bowell

Table 3. Dynamical evolution over a time span of 821.4 years of *1995 QY_2*: (top) orbital parameters at the starting point of the integration (first line) and every 50 000 days, from JD 2 300 000.5 to JD 2 600 000.5; (middle) close encounters with planets; (bottom) possible librations about mean-motion resonances with the giant planets.

1995 QY2

Orbital parameters

1996 1 18	1996 1 25.4	3.11965	0.57256	266.309	147.361	20.434	53.422	−20.390
Epoch	*T*	*a*	*e*	ω	Ω	*i*	*L*	*B*
1585 2 1	1586 10 26.7	3.12202	0.55075	243.871	172.202	22.453	54.245	−20.053
1721 12 25	1719 5 31.3	3.14933	0.55290	249.563	165.945	21.384	54.135	−19.978
1858 11 17	1857 9 9.0	3.11219	0.56906	256.633	157.881	20.893	53.611	−20.301
1995 10 10	1996 1 25.4	3.11932	0.57251	266.308	147.361	20.434	53.422	−20.390
2132 9 1	2134 3 12.1	3.15532	0.56291	272.792	139.899	20.349	52.876	−20.324
2269 7 25	2266 12 14.3	3.11484	0.57323	281.034	130.772	20.889	52.561	−20.485
2406 6 17	2405 7 29.3	3.12638	0.56456	290.334	120.711	21.858	52.478	−20.432

Close encounters (Outer planets: $d < 0.50AU$, Inner planets: $d < 0.05AU$)

None within the given distances

Possible librations about the following resonances

Planet	*Epoch*	*Resonance*
Jupiter	1585 – 2406	15/7

IAU designation: 1995 QY2 Number of revolutions in the integration interval: 149
Reference orbit: Bowell

appartenance to a taxonomical class as a function of the spectral slope, we have obtained the following results:

(6042) *1990 WW_2*

The spectrum of this object has been obtained on 12 Nov. 1995 with an exposure time of 1^h at an air mass of 1. It is completely featureless and the slope S' we have computed is 7.6 ± 0.1%/1 000 Å. This value is near the lower limit (7%) of D-class objects.

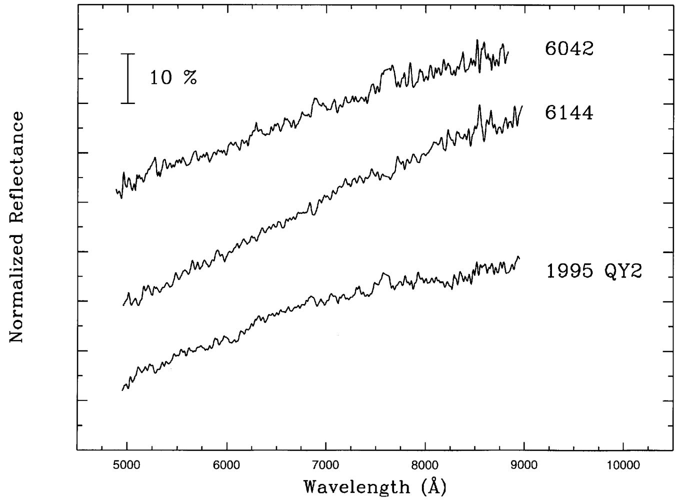

Fig. 4. Optical reflectance spectra (normalized at 7 000 Å) of asteroids (6042) *1990 WW_2*, (6144) *1994 EQ_3*, and *1995 QY_2*.

(6144) *1994 EQ_3*

The spectrum of this dynamically peculiar object has been obtained on 17 Apr. 1994 with an exposure time of 1^h at an air mass of 1.2. It shows the larger slope among those we have analyzed. The computed value of S' is 10.4 ± 0.1%/1 000 Å, which is near the upper limit observed for D-class objects and very similar to the spectral slopes of comets 49P/Arend-Rigaux, 2P/Encke, and 21P/Giacobini-Zinner, 9.3%, 11%, and 12.8%,respectively (Luu, 1993). These spectral characteristics agree with the conclusions drawn from the dynamical analysis (see previous Section) about a cometary or Trojan origin for this object.

1995 QY_2

Spectrum of this object has been obtained on 14 Sep. 1995 with an exposure time of 40^m at an air mass of 1.02. This spectrum is flat downwards about 6 000 Å and increases steeply afterwards. The value of S', computed from 6 000 to 9 000 Å, is 10.0 ± 0.1%/1 000 Å, compatible with that of D-class asteroids and, as in the case of (6144) *1994 EQ_3*, with those of cometary nuclei.

4. Conclusions

We have presented and discussed dynamical and spectral properties of 3 dark asteroidal objects. The dynamical behaviors of these bodies are considerably different. (6042) *1990 WW_2* has a high-inclination orbit and, during the period in which has been analyzed (821.4 years), it does not show any large variations in semi-major axis, aphelion and perihelion distance.

(6144) *1994 EQ_3* shows a very irregular orbital evolution: it undergoes several close encounters with Jupiter and its semi-major axis changes very rapidly. According to its dynamical behavior, this object could be an Edgeworth-Kuiper Belt comet or a fragment of a recent family-forming event in the Trojan cloud. This last possibility is suggested by the fact that 3 clones of its actual orbit, integrated backward in time, are trapped in Jupiter's *horseshoe* orbits for more than 10^4 years.

Table 4. Aspect data of the observed asteroids.

Object	Date [0 UT]	R.A. [2000.0]	Decl. [2000.0]	Long. [2000.0]	Lat. [2000.0]	r [AU]	Δ [AU]	α [deg]	V [mag]
6042	1995 11 12	$22^h30^m.5$	$-32°$ 42'.0	326°.11	$-21°.6$	1.68293	1.24419	35.7	15.5
6144	1994 04 17	12 53.7	+03 09.3	190.40	+08.2	3.03131	2.05962	05.8	15.3
1995 QY_2	1995 09 14	21 50.6	-10 15.2	325.62	+02.6	2.10141	1.09129	02.9	15.6

1995 QY_2 is a Mars crosser and librates about the 15/7 mean-motion resonance with Jupiter. However, the resonance trapping is not stable and small variations of its orbital parameters can generate different orbital evolutions after the resonance escape: 9 over 15 clones of the original orbit jump on several other resonances with Jupiter and some of them become Earth crossing before the end of the integration. 6 clones end up in Jupiter-crossing orbits on a timescale of the order of 10^5 yr and, from a dynamical point of view, they become comets.

These dynamical differences do not correspond to strong spectral differences: all spectra show the typical trend of carbon-rich, low albedo, "primitive" objects and are compatible with those of outer-belt asteroids. Results seem to confirm the hypothesis that some low-albedo objects could have cometary origin. In particular, the relatively high redness of (6144) *1994* EQ_3 (similar to that of three comet nuclei), coupled with its peculiar dynamical characteristics, support the hypothesis about a possible cometary origin of dark asteroids, which could be exhausted comet nuclei.

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