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Satellites of asteroids

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Abstract. More than 6000 asteroids in the Solar System have now been discovered and enumerated, and about 500 of them have been investigated in detail by different methods. This review gives observational evidence which indicates that no fewer than 10% of asteroids may be composed of two or more bodies. This was supported by the detection of a satellite of the asteroid Ida by the Galileo spacecraft. This discovery symbolises the change of both observational and theoretical paradigms. Space and ground observations of asteroids by modern techniques may give extensive new data for modelling double asteroids. The analysis of problems of stability, formation and dynamics of asteroid satellites shows that their sphere of stable motion extends up to several hundred asteroid radii. The idea that the origin of the asteroid satellites may be explained in the frame of a unified accretion model of planetary satellite formation is proposed and justified.

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1. Introduction

In February 1994 sensational information was received from the interplanetary spaceprobe Galileo: asteroid Ida has its own satellite (see Fig. 1). It was detected during two independent experiments [1, 2]. This became one of the fundamental discoveries in the many centuries of history of studies of the Solar System. This really sheds a new light on asteroids and on the cosmogony of the Solar System.

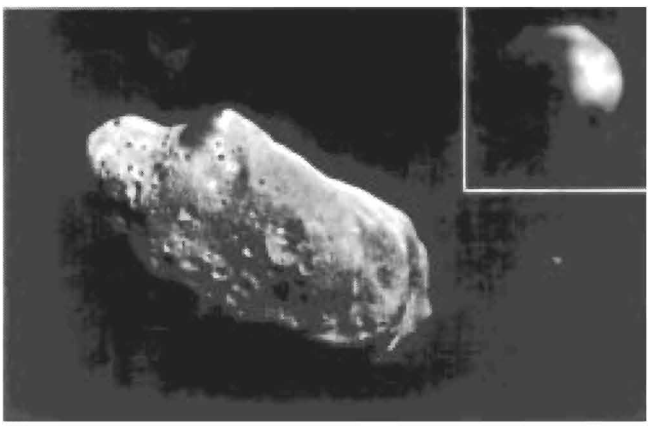

Figure 1. Image of asteroid 243 Ida and its satellite sent to Earth from the Galileo spacecraft. The satellite is seen as a small point to the right of the asteroid. At the top right a zoomed view of the satellite is given.

Asteroids, or minor planets, together with satellites of large planets, comets and meteoroids, constitute an extensive class of small bodies in the Solar System. These bodies appear to be eyewitnesses of the early evolution of the Solar System, and they hold information about the composition of the original matter of the protoplanetary cloud. Most of the minor planets are located between the orbits of Mars and Jupiter, in the main asteroid belt. This belt has a complex spatial structure and undergoes continuous dynamic evolution due to the gravitational influence of the large planets. The border line between different types of small bodies is very fuzzy. Many of the large planets' satellites cannot be distinguished from asteroids by means of their physical properties and sizes. On the other hand, some asteroids, like comets, have observable signs of gas ejection, and many comets, having been covered by a rigid crust during evolution, are in turn indistinguishable from asteroids. There is also no sharp border line between asteroids and meteoroids, because their sizes vary from about one kilometre to a fraction of millimetre (micrometeoroids). Meteor streams, consisting of micrometeoroids and dust particles, which enter the terrestrial atmosphere, may be related either to comets (the more usual case) or to asteroids. Thus, a general picture of the close connection between all members of the Solar System takes shape.

Over recent years asteroids have been the main source of sensational discoveries in our planetary system. Firstly, first representatives of the second asteroid belt were found near the orbit of Pluto. Their diameters are several hundreds of kilometres [3, 4]. Secondly, numerous ground-based observations give evidence for asteroids with complex structure, either double or possessing satellites [5]. Thirdly, the first direct images of asteroids — Ida and Gaspra — were obtained from space [2]. Fourthly, a large number of small bodies were found with orbits approaching very close to the planets, which in the case of Earth presents a potential threat to the very existence of the biosphere [6]. The problem of danger from asteroids has lost its abstract nature since the impact of comet Shoemaker – Levy with Jupiter in July 1994. That created a mighty cataclysm in the Jovian atmosphere which was the subject of serious discussions in scientific and political circles [7, 8]. This is the reason why 1994 has become possibly the turning point in the development of the science of asteroids.

This review is devoted to the analysis of this new situation. Based on a review of publications, observations and our own research, we will

— present observational data supporting the existence of asteroid satellites;

— demonstrate different ways of studying this type of object using new approaches to data processing and interpretation;

— analyse the theoretical possibility of the existence of multicomponent asteroids;

— examine the implications of the complex structure of asteroids for the present day picture of Solar System formation.

We restrict our attention to two aspects of the 'asteroid revolution'. First, the widespread point of view that asteroids are single bodies of different sizes needs to be revised. The double nature of asteroids or the presence of satellites is not a unique but rather a typical phenomenon. Second, asteroids must be considered in parallel with the large planets in the frame of general theories. This relates both to the problem of the formation of systems of satellites and to that of asteroid evolution in general.

2. History of the discovery of asteroids and a short review of their properties

As long ago as the beginning of the 17th century Johann Kepler suggested that there must be some planet between Mars and Jupiter. It was discovered by chance by Piazzi on 1 January, 1801. By 1807, however, three more planets had been discovered. They were named Ceres, Pallas, Juno and Vesta. They have diameters of 1003, 608, 247 and 538 km, respectively. It turned out that instead of one large planet there are many minor planets named asteroids (which means starlike) after their appearance, which fill the space between Mars and Jupiter. Up to now more than 6000 asteroids have been discovered and have had the elements of their orbits determined. They also possess names and catalogue numbers. At first, every newly discovered asteroid was traditionally given the name of a woman from Greek – Roman mythology. Asteroids which appear to be distinguished by their orbital motion have male names, for example the Trojan group or the Amor group. As the total number of asteroids discovered increased, the choice of names came to be determined by the fantasy of the discoverer followed by official affirmation by a special commission of the International Astronomical Union and designation by number. According to some estimates, probably no fewer than one million asteroids exceeding one kilometre in diameter exist in the Solar System. Their total mass is about 5×10^{24} g.

The majority (99.8%) of asteroids are concentrated in a torus-shaped main belt between Mars and Jupiter. The major semiaxes of their orbits lie within 2.06 – 4.09 AU, the mean semiaxis is 2.7 AU, the mean eccentricity is 0.14, the mean inclination is 9.5°. Orbital velocities of asteroids are about 20 km s^{-1}, and their periods of rotation lie between 3 and 9 years. The main asteroid belt has a complex inner structure. There is stratification into several overlapping rings, the presence of separate families, groups, and jet streams with similar dynamic or physical characteristics [9 – 11]. Complex gravitational influences of the large planets result in slow variations of orbits of individual asteroids in the belt although these orbits have been in general stable for 4.5 billion years. The main role in this process is played by the resonance action of Jupiter which has emptied vast regions of the space between the major semiaxes (Kirkwood gaps), so that there are practically no bodies with orbital periods which are multiples of 1/2, 1/3, 2/5 or 3/7 of the Jovian period. Intercollisions of the asteroids also result in variations of their orbits, disintegration or transfer to another family or group. Since families are dynamic formations, they have a rather small age, and their origin is likely to be related to asteroid collisions. Therefore they consist of one or two large bodies and a great number of small ones. The families are named after their largest member.

When considering asteroids lying beyond the main belt it is worth noting the belt beyond Pluto. There is also an interesting population of small bodies which have diameters up to 150 – 200 km situated between Jupiter and Uranus [12]. Among them, Chiron was the first to be discovered. It had been thought to be an ordinary asteroid until it was

shown to eject dust and gas like comets [13]. It is also necessary to include the very important group of asteroids which experience close approaches to Earth, along with comets and meteoroids.

For a long time, studies of minor planets were limited, in general, just to their discovery and orbit determination. Their physical investigation was carried out rather haphazardly. Little by little it became clear, however, that all but the largest asteroids have an irregular shape and a rather uneven surface covered by impact craters. The distribution by period of axial rotation for 249 large (diameter >55 km) asteroids and for 267 small ones was analysed in Ref. [14]. This distribution is described by two maxwellian functions for large asteroids and by three functions for small ones. Their mean values were found to be, respectively:

7.69 h for 2/3 of the large asteroids
11.82 h for 1/3 of the large asteroids
7.62 h for 2/3 of the small asteroids
19.51 h for 13% of the small asteroids
3.88 h for 21% of the small asteroids.

Authors came to the conclusion that the 66% of asteroids with periods 7.6 – 7.7 h represent the original population, whereas the other asteroids have experienced catastrophic collisions.

Analysis of the polarisation of solar radiation scattered by asteroids shows that the surface of many of them is probably covered by a regolite, a scattered substance which was formed as a result of frequent collisions of the asteroid with small bodies and tiny particles. The reflecting ability of asteroid surfaces strongly varies at different wavelengths. This implies a diversity of composition of asteroids. 75% of asteroids are assigned to class C (carbonaceous). They reflect only 3% of the incident solar light, so their albedo is 0.03. Lighter asteroids of class S (stony), which includes about 15% of all asteroids, have albedo 0.15. Asteroids of different classes are not intermixed and tend to concentrate at definite heliocentric distances. For example, light S-asteroids tend to concentrate in the inner part of the belt and dark C-asteroids in the outer part of the belt, so there has been no significant intermixing between them during the time of their existence (4.5 billion years). This means that in the protoplanetary gas and dust cloud the stratification of matter had already taken place in accordance with its atomic and molecular masses.

At the present time, different types of asteroid classification have been developed which include from several up to 15 classes [15 – 18]. Each class is characterised by a definite set of physical parameters — such as albedo, colour index, mineral compositions — and by their magnitudes. Some classes coincide with those for meteoroids whose composition is well known. The mineral composition of asteroids is rather diverse. Some of them contain a large amount (up to 50%) of bound water. Both the main belt asteroids and the asteroids from the belt beyond Pluto may (like comets) also contain the volatile components of protoplanetary clouds. Like comets, some asteroids (of S-class and similar) may have at their surfaces thin layers of primitive organic substances originating under the action of radiation. There also exists a rather poorly populated class M of asteroids which possess high metal abundance. The classification of asteroids is based on data for about 30% of all known asteroids and is far from complete.

3. Observational data on the binarity of asteroids

The development of our understanding of small bodies in the Solar System is largely defined by the methods and tools of observations which are available at a given moment of history. For the observers in the 19th century, asteroids looked like point sources through the telescope. This is the reason for the general acceptance of the idea of asteroids as single bodies. However, at the beginning of the 20th century, the first investigation of asteroid 433 Eros was carried out, which gave evidence for its binarity based on the visual observations of its brightness. It was followed by a few visual and photographic observations supporting the idea of binarity of asteroids. But these results were met with some doubt and did not attract much attention — they were in explicit conflict with the general opinion. Several decades of different types of observation and theoretical studies had to pass for the general opinion to be changed. We consider below what tools and possibilities modern science and technology offer for investigators and what the real possibilities are of getting information about the binarity of some asteroids.

3.1 Image detection of asteroids and their satellites

In this section we will consider results and perspectives of studying the complex structure of asteroids using different methods based on visual and photographic observations, as well as on the observations made with electronic optical image detectors. The speckle-interferometric method of obtaining information from under the scattering function of the terrestrial atmosphere, which was developed over the last few decades, increases angular resolution for ground-based observations, practically to the resolution of the telescopes themselves.

3.1.1 Requirements for direct image detections

The problem of studying asteroid structures by direct image detection is rather complicated, because the components have small angular separations, less than one arcsecond, and also have brightness differences which may be too high. For example, Ida's satellite is several hundred times fainter than the central body. Therefore there are three requirements for high sensitivity which must be satisfied by detectors: high angular resolution, high dynamic range and the ability to detect the image of a fainter component close to a bright one. For ground-based observations, the first requirement is fulfilled by using large telescopes situated in such sites on Earth where the absence of strong atmospheric turbulence allows one to obtain images of celestial bodies with angular resolution down to some tenths of an arcsecond. Series of observations supported by modern equipment which were carried out in recent decades in Hawaii and the Canary islands, in Chile and other places with perfect astroclimate have practically exhausted our attempts to increase angular resolution by choosing the best sites for observations. The problem of increasing angular resolution further is now being solved by using more sophisticated methods of data processing.

The two other requirements refer to the light detector in use, so they are partially interrelated: one cannot detect a faint image close to a bright one unless a wide dynamic

range of the flux-signal parameter is provided. In addition, the scattering inside the detector of light from a bright source and the broadening of its image which takes place in photographic and in some electronic optical image detectors must be excluded.

3.1.2 Visual, photographic, and electronic observations

Extended shapes of some asteroids were sometimes noted by experienced visual observers. The first announcement of this type which claimed the binarity of two asteroids was published in 1926. By measuring the separations between components of visual double stars in the range of 0.18–0.30 arcseconds with the 26.5 inch telescope of Johannesburg Observatory, 'new double stars' with a separation of about 0.2 arcseconds were discovered, which turned out in fact to be asteroids 433 Eros and 2 Pallas [19]. During Eros' closest approach to Earth in 1931 its distance was only 28 million km. Observations by telescope revealed its elongated shape, like a dumbbell or a double star, with a separation of 0.18 arcseconds which corresponded to about 28 km.

Currently, visual observations are not used because they are believed to be rather subjective. At the same time, the quantum efficiency of modern electronic light detectors is approaching that of the human eye, so the need to use the eye as a physical device is gradually disappearing.

In 1979–1980 photographic observations of asteroid 9 Metis were carried out in the high mountain Chinese observatories Purple Mountain and Yunann when the asteroid was at a distance of 1.23 AU from Earth. These observations were obtained with 0.6 and 1.0 metre telescopes during 13 nights using photoemulsion 103aO [20]. A series of eight photographs with a sufficiently high angular resolution was obtained during 7 nights. The separation between the components varied from 0.93 to 1.2 arcseconds. The position of the satellite image changed with time, which made it possible to determine the period of the satellite's rotation around the asteroid, 4.61 days, its major semiaxis of 1100 km and coordinates of the orbital pole which appeared to be close to the coordinates determined for Metis's axis of rotation. The total mass of the system was estimated to be 5×10^{21} g, and its mean density 2.5 g cm^{-3} assuming Metis's diameter is 153 km. The satellite's diameter was estimated to be 60 km from the brightness difference of 2 magnitudes between the components. This value is in a good agreement with the diameter estimate of 65 km obtained from a star occultation on 11 September 1979.

It is worth noting that the photographic method was not stretched to its limit in that case. There exist special 'deep' photoemulsions such as Kodak IIIaJ which are widely used for observations of faint stars against the night sky background. Their threshold contrast is 0.02 which is three times better than the 103aO emulsion used by the Chinese astronomers [21, p. 179]. Such emulsions permit the detection of quite low contrast images in spite of lower sensitivity. Their use for observations at large telescopes situated in sites with a good astroclimate may result in obtaining pictures of satellites of some asteroids at the most favourable moments for such observations.

A search for asteroid satellites on photographs of the sky was carried out by Gehrels et al [22]. They used asteroid survey data from the York–McDonald and Palomar–Leiden observatories with limiting magnitudes 16.5 and 20.6, respectively. At a distance of 2.6 AU, this allowed them to detect marginally objects with a size of 17 and 3 km having a geometric albedo of 0.06. A search for faint images of satellites was carried out for 10 asteroids at distances from six arcseconds to seven arcminutes. The lower limit (6 arcseconds) was determined by the rather low angular resolution of the photoplates used. The authors came to the conclusion that if asteroid satellites really exist, they must be very close to their parent body. The best candidates for binarity they found were 624 Hektor and 216 Kleopatra.

Electronographic cameras, which provided astronomers with unique observational data for several decades, possess a high quantum efficiency and allow the reliable detection of low-contrast images down to a contrast threshold of 0.5% [20, p. 179]. Use of an electronographic camera, in which every single photoelectron may be detected, allows the detection of large brightness differences of close objects. The simplicity of the physical principles of the electronographic camera and its successful implementation in France, Britain and the USSR gave astronomers low-noise devices approaching the ideal light detector with quantum output equal to that of a cathode with external photoeffect.

The high quality of transformation of the optical picture to the electronic image makes this technique rather promising for asteroid satellite detection. One can be sure that the use of such equipment with a telescope located in a site with good astroclimatic conditions to provide high angular resolution could give exciting results. Now there are few such devices left in the observatories. The complexity of their exploitation, the deficiency of electronographic emulsions and difficulties of extraction of photometric information from the images obtained forced astronomers to seek for new methods. The appearance of CCDs, which are one of the modern types of solid state light detectors, has practically displaced the electronographic camera from the field of astronomical observations, although, undoubtedly, there are some problems left where its use is highly appropriate. One of these problems is searching for asteroid satellites where the key point is to obtain an image of a faint satellite close to a much brighter asteroid.

3.1.3 Television and CCD observations

By definition, TV light detectors are devices that facilitate remote transmission of optical images by radioelectronic means. A system of TV transmission fulfills the following functions: transformation of an optical image in the focal plane of the telescope into a temporal sequence of electrical signals, or videosignal; transmission of this signal for some distance (for example, from the focal plane of the telescope to recording devices) by radioelectronic means; inverse transformation of the videosignal into an optical image. The latter procedure may be carried out not in real time, but after an additional processing of the videosignal, which is recorded and kept in digital code in the computer memory during observations. From this general definition of TV systems it follows that the widespread CCDs are essentially representatives of TV-type devices: they are characterised by all three above-mentioned transformations.

TV systems used for astronomical observations are subdivided into two classes depending on the type of photoeffect — internal or external — used in the light detector [21]. The first class includes all vacuum transmit-

ting tubes; the second all solid state transmitting devices, both two-dimensional (matrices) and one-dimensional (lines).

The necessity to transform the optical image into a sequence of electrical signals complicates the recording system as a whole, which leads, in comparison with the electronographic camera, to some restrictions on obtaining the image of a faint object close to a bright one. The reasons for these restrictions are different for different types of devices, but they always involve increase of the bright image size (diffusion), presence of a halo (which may be dark) or diffusion of the image along the line of information readout. This shortcoming of TV devices must be kept in mind when the problem of direct asteroid satellite detection is considered. However, the advantage of this method is the possibility of using different image processing programs on the star fields, which allows one to detect automatically any object moving with respect to the stars and to introduce all kinds of image restoration, including profile restoring of close stars with partially overlapping images; this outweighs its shortcomings.

Owing to their high quantum efficiency, wide dynamic range, the possibility of registration of low (fraction of percent) contrasts and computer data processing, TV light detectors and especially CCDs are certainly very promising devices for studying double asteroids.

The first experiment using CCDs for searching for satellites of 10 asteroids brighter than 10 magnitudes was carried out in 1984–85 with 0.9 and 1.54 metre telescopes in the USA [22]. The RCA CCD had 320×512 pixels (photosensitive elements) of $30\ \mu m \times 30\ \mu m$ in size. It could reach limiting magnitudes from 22 magnitudes to 18 magnitudes depending on the telescope used and its focal length. Different focal lengths were used which allowed variation of the angular resolution. To get rid of noise related to image diffusion along the readout line, every field of search was exposed at least twice with the matrix turned by 90° around the line of sight. The authors noted the presence of a halo around the bright image 38 pixels in size. Undoubtedly, atmospheric diffusion and light scattering in the telescope were also nuisance factors. They all certainly reduced the registration threshold for faint objects in the near vicinity of the asteroid.

This experiment revealed all the difficulties of such searches. For the detection of satellites to be successful specially prepared equipment and a telescope with low light scattering must be used. As a rule, the halo brightness caused by light scattering in the telescope's optics is about one percent. The atmospheric scattering is usually more annoying, so these observations must be carried out on extremely good nights. Shortcomings of the CCDs appearing as diffusion of bright images can be overcome only by using a special adjustment which moves an artificial moon into the focal plane in order to deflect the main light beam of the asteroid under study.

3.1.4 Speckle interferometry

About twenty years ago a new method for improving angular resolution for ground astrophysical observations with large telescopes was developed — speckle interferometry. Optical inhomogeneities of the atmosphere between the object under investigation and the telescope lead to a speckle structure of the stellar image obtained with a short exposure of some hundredths of a second within a sufficiently narrow wavelength interval. The technical opportunity for registration of speckles was provided by the development of various high sensitivity photoelectric light detectors which made possible a reliable detection of the speckle image structure for large focal length telescopes. Coherent optics advances and the speckle structure investigation of a scattered light field allowed Laberie to formulate the physical principle of speckle interferometry in 1970 [23] and to carry out the first speckle observations of stars with a 5 metre telescope two years later [24].

Initially, the speckle pictures were registered by photography taken from the screen of the image tube [25]. Later on, TV systems were developed to perform real-time image processing by computer. The TV digital speckle interferometer developed for the 6 metre telescope [26] allowed numerous investigations of double stars with separations between the components from 0.812 to 0.025 arcseconds, with a mean square error of 0.0026 arcseconds and brightness difference less than 3 magnitudes [27]. The limiting magnitude is about 16 magnitudes for large telescopes [28], which allows the detection of satellites of the asteroids of the main belt if their size is a few dozens of kilometres.

Some experience of asteroid observations has been obtained at the 2.3 metre telescope of the Steward Observatory (USA). The diffractional resolution of the telescope was 0.05 arcseconds, and the mean square error of size determination was about 0.01 arcseconds. According to Ref. [30], binarity has been confirmed for asteroids 2 Pallas and 12 Victoria. Asteroid Eros has not revealed unambiguous component separation, although the authors managed to obtain the size of the asteroidal body: it was found to be $40.5\ km \times 14.5\ km \times 14.1\ km$ with a mean error of 2.5–3 km [31]. This result is in accordance with previous size determinations. Observations of 532 Herculina showed its dimensions to be $263\ km \times 218\ km \times 215\ km$. No satellite with diameter exceeding 50 km was found, which in that case corresponded to the detection threshold [32].

Thus, speckle interferometry studies showed that in spite of the promising possibilities of this new and rather sophisticated method it still cannot reliably detect the binarity of asteroids. This is because of limitations of the method, including the problem of observing a faint object close to a bright one. Hence, to observe satellites it is a good idea to choose those asteroids where one may expect a rather bright satellite to be present, and rather slow axial rotation, permitting a long series of speckle-interferometric observations.

3.1.5 Radiolocation

Radiolocation of asteroids has became feasible now that powerful radiotransmitters and big radiotelescopes have been constructed. The time delay of the echo signal allows the measurement of the distance to the object, and the Doppler frequency shift gives information about its velocity. A 70 m radiotelescope permits linear resolution up to tens of metres in the direction of radiolocation [33]. Rotation of asteroids widens the reflected echo signal. These observational data provide information concerning the shape of the asteroid [34, 35].

The first echo signal from an asteroid was detected in 1968 by an American team [36]. The object of observation was chosen to be asteroid 1868 Icarus when it was at a

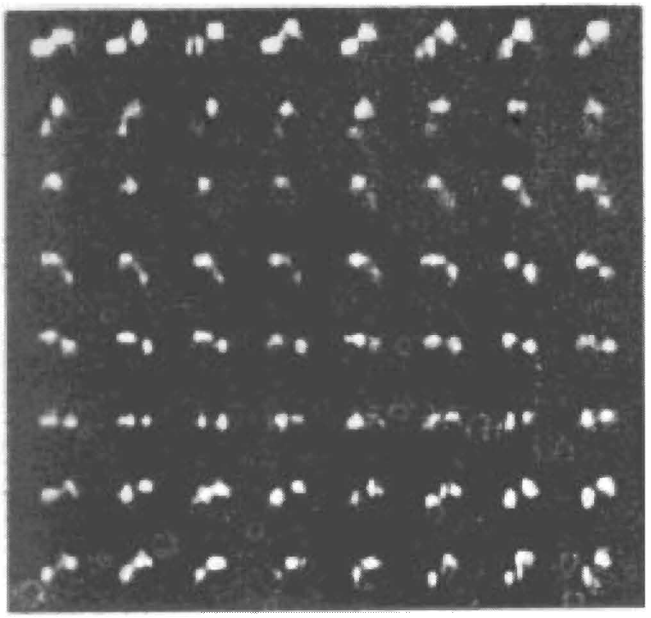

Figure 2. 64 consecutive radioimages of asteroid 4769 Castalia.

distance from Earth of 0.04 AU. By the middle of 1993, radar observations of 37 asteroids from the main belt and 32 asteroids approaching Earth had been carried out [33]. The time delay of the echo signal and its Doppler broadening can be used to create a quasi-image (radioimage) of the asteroid under investigation, where the lag time is along the vertical axis (with the radar conventionally placed above) and the frequency of the reflected signal is along the horizontal axis. The third coordinate is the intensity of the signal, analogous to the brightness of the image. Observations of the asteroid 4769 Castalia in August 1989 when it was at a geocentric distance of 0.037 AU gave evidence for its binarity and allowed its rotation to be traced during almost the total period of 4.07 hours, as is clearly seen in Fig. 2. Ostro et al. [37] found its size to be 1 km × 1.7 km and density 2.6 g cm^{-3}. They concluded that this is a contact or near-contact system: if its components are separated, then the distance between them does not exceed 100 m.

In December 1992, asteroid 4179 Toutatis reached a minimum distance of 0.024 AU (3.6 million km) from Earth. It was discovered in 1989 and was named after the Gaulish tribal god who was responsible for their prosperity. From the elements of its orbit it was calculated that this asteroid approaches close to Earth regularly every four years, so various observational methods were used for its investigation. Radiolocation was carried out by two scientific groups [38, 39]. Fig. 3 shows radioimages of asteroid Toutatis obtained by Ostro et al. [40]. Two components and their irregular shapes are clearly seen. On 8 and 9 December, radiolocations of this asteroid were carried out in Europe as well [39]. The planetary locator of the Centre for Remote Space Communication installed near Eupatoria, Crimea, sent radio signals which were echoed and received by the 100 m array in Effelsberg, Germany. Hydrogen frequency standards provided both good coordination and high precision of measurements, so the line-of-sight velocity error was 0.03 mm s^{-1}. The signal reflected by the asteroid showed two maxima (see Fig. 4) indicating a

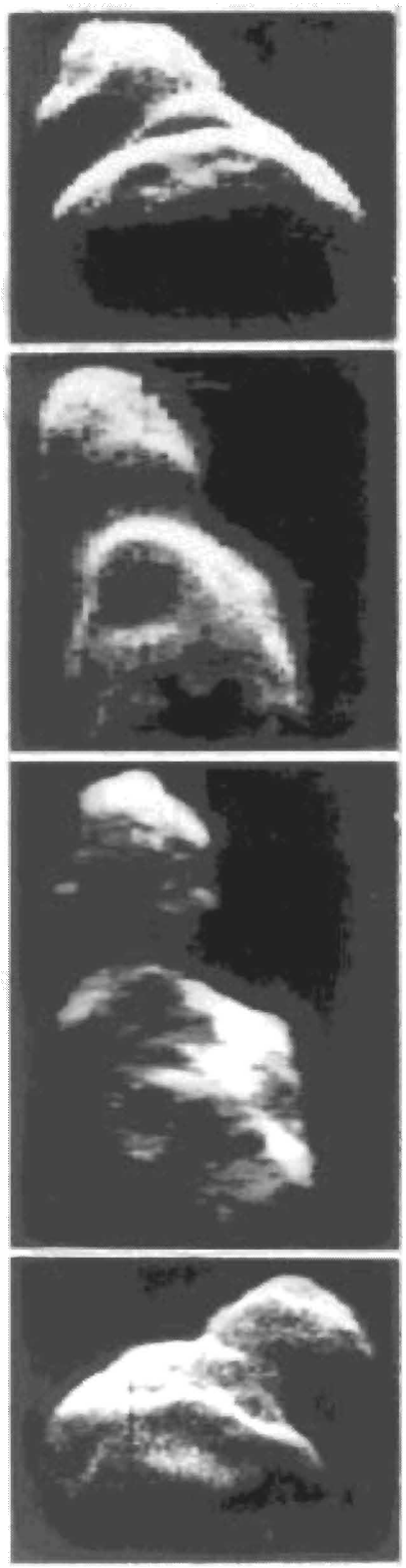

Figure 3. Radioimages of asteroid 4179 Toutatis obtained by Ostro et al. [33] on 8, 9, 10 and 13 December, 1992.

binary structure of this object. Comparison of the energies confined in these spectral features separated by the minimum allowed estimates to be made of the relative sizes of both components of this system. From the data obtained on 8 and 9 December, the cross sections of the smaller component in the plane of the sky were found to be

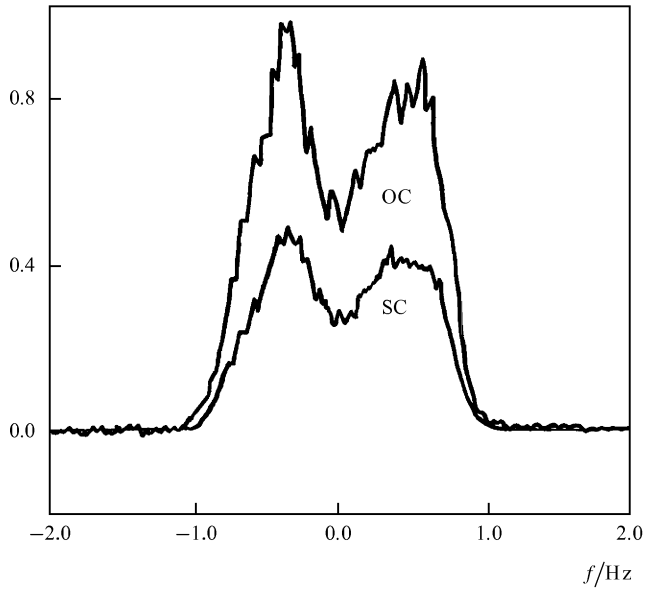

Figure 4. Power spectra of the echo signal from asteroid 4179 Toutatis obtained during its location by a group of European scientists [39] on 9 December, 1992. The signal OC for polarisation in one direction is normalised to unity, whereas the signal OS for polarisation of the opposite rotation is normalised to 0.5.

70% and 85% of that of the larger one, respectively. The authors proposed that the components were partially overlapped in projection on 8 December. The density of the surface layer of the asteroid was found to be 1.5 g cm^{-3}. Zaitsev et al. [41, 42] were the first to pay attention to the fast quasiperiodical variations of the signal reflected by the asteroid which they interpreted as a result of the interference of the echo signals reflected by the two components. In the case of a binary asteroid, the echo signals reflected from some regions of the components' surfaces must have identical radial velocities, which leads to interference between them for some orientations of the components with respect to the direction to the locator.

The method of radiolocation is without doubt a very promising one for studying the complex structure of asteroids, although no clearly separated echo signals from the components of known asteroids have been received as yet. Eight out of the 69 asteroids which were investigated by radiolocation (about 10%) showed evidence for double structure at different confidence levels [33, 43–45], with the discovery of their binarity being unexpected in most cases. It should be borne in mind that two components of an asteroid will be clearly detected once their sizes are comparable and large enough to provide certain echo signals, while their line-of-sight velocities are different. As Ostro pointed out [33], during ten years' observations, the radioarrays of the Arecibo and Goldstone observatories were able to estimate the total number of double asteroids belonging to the group intersecting Earth's orbit. Note also that observations of small asteroid satellites by modern radiolocation devices are unlikely to give positive results.

3.1.6 Observations from spacecraft

A program of asteroid observations from spacecraft was developed more than twenty years ago. Its aim is to obtain scientific data which are not available from ground observatories. These plans were fulfilled to a large extent, so our knowledge has been significantly enlarged. In particular, it is worth remembering that the albedoes and diameters of about 2000 asteroids were found from infrared observations, and spectral observations of asteroids in the ultraviolet and infrared regions were also achieved.

The launch of the interplanetary spaceship Galileo gave an opportunity to carry out unique observations. In 1991 for the first time a photograph of an asteroid which the spacecraft went past at the close distance of 16 000 km was obtained. It was the rather unremarkable asteroid 951 Gaspra discovered in 1916 by the Crimean astronomer Neuimin [46] and named after Crimean settlement Gaspra near the city of Yalta. In August 1993 the spacecraft Galileo passed by asteroid 243 Ida [1, 2]. The picture of this asteroid was received on Earth in August 1993, but the accompanying information was stored for several months on board the spaceship because of the complexity and long duration of the transmission of information through the telemetric channels. Therefore the photograph of Ida and its satellite was obtained only in February 1994. The presence of a satellite was totally unexpected. It was detected by two independent devices including an on board matrix TV system (see Fig. 1). According to Morrison's report at the 22nd General Assembly of the International Astronomical Union, the satellite Dactil is 1.6 km × 1.4 km × 1.1 km by size, and nearly spherical in appearance. Its spectrum (and chemical composition) is evidently different from the main asteroid. The latter is 56 km × 24 km × 21 km in size and rotates with a period of 4.63 h. The orbit of Dactil is circular with a radius of 90 km. The period of revolution is nearly one day. The orbital plane lies close to Ida's equatorial plane.

Observations of Ida were serendipitous in some sense — it just happened to be close to the trajectory of the Galileo spacecraft which was on its way to Jupiter. It is impossible to plan similar investigations for a large number of asteroids because of the large cost of such experiments. That is why it is appropriate to develop a programme of investigations of asteroid structure from space using some other available method. For example, orbital telescopes, especially the Hubble Space Telescope, provide images of astronomical objects with an angular resolution which is much higher than that of ground telescopes. Atmospheric turbulence does not interfere with observations from space, and up-to-date technology enables one to obtain high quality images. Certainly, these are expensive observations, so they must supplement those studies which are carried out in the ground-based observatories with the best astroclimatic conditions.

There are also some plans to land a spacecraft on the surface of one of the asteroids. The aim of the landing is to study the surface composition, seismometry, gravimetry, to obtain direct surface temperature measurements, and possibly to probe the soil to bring a sample to Earth for further analysis. The possibility and permissibility of a space mission to deliver a nuclear charge to the surface of an asteroid to induce a nuclear explosion are also discussed [8]. The discovery of satellites of some asteroids and the binarity of some others allows a fresh look at the problem of spacecraft landing on asteroids.

3.2 Occultations of stars by asteroids and other evidence for asteroid binarity

Here we will consider the results of numerous observations obtained during the crossing of asteroids between the observer and some star (stellar occultation); we will also briefly analyse a genetic relationship between asteroids and comets with a complex structure which has revealed itself over recent decades, and will examine another factor indicating the binarity of asteroids: the existence of double craters.

3.2.1 Star occultations by double asteroids

For a long time, occultations of stars by asteroids (which may be considered as eclipses which can be observed from certain sites on Earth) did not attract much attention because computational methods could not provide useful and accurate calculations. However, since 1975 these observations have become widely used for measuring diameters of asteroids [48, 49]. The results were unexpected: they showed that stars were occulted twice or more times instead of once as if not one but several bodies had intersected the ray path between the star and the observer [50, 51]. These results are highly reliable: usually, the observations are carried out not only by professional astronomers but also by numerous experienced amateurs situated inside the eclipse strip or in the vicinity of it. This increases the value of the observations because the size and visibility conditions of the shadow may be used to recover the shape of the occulting body [52]. McMahon observed several transient occultations of a star by asteroid 532 Herculina before and after the main occultation which lasted about 20 seconds. The sizes of the bodies which were responsible for the secondary effects appeared to be less than the sizes of the asteroids. This was reason to propose that they are asteroid satellites [54]. Observational data obtained by several observers allowed an estimate of the sizes of the largest satellites: 20 km for Hebe and 46 km for Herculina, the latter being separated by 1000 km from the asteroid [51].

Revision of results of earlier observations of star occultations by other asteroids gave evidence for possible satellites for asteroids 2 Pallas, 3 Juno, 6 Hebe, 9 Metis, 12 Victoria, 129 Antigone, 433 Eros and also 18 Melpomene [49]. In the latter case three independent photoelectric and one visual observation performed in 1978 detected several secondary occultations in addition to the main one. A conclusion was made that in addition to the largest satellite, moving at a distance of at least 750 km from the parent body, a cloud of small bodies with sizes of about 300 m [9, p. 91, 52] exists. Hartmann in Ref. [54] presents some more asteroids suspected to be binary: 44 Nisa, 49 Pales, 171 Ophelia, 24 Hektor. In 1982 in Meudon Observatory (France) simultaneous observations of a stellar occultation by the asteroid 146 Lucinia were carried out by different methods including a TV camera. As a result, a satellite of 6 km in diameter was discovered at a distance of 1600 km from the centre of the main component [55].

Results of asteroid satellite detections when they occult stars were evidence for the existence of asteroids with a complicated composite nature. So Binzel and van Flandern [49] appear to have been right when they claimed in 1979 that the presence of asteroid satellites is normal, and that this kind of object should be rather numerous.

3.2.2 Complicated structure of comets

The close resemblance between asteroids and comets, which is well known to exist, cannot be a pure coincidence [56, 57]. Their dynamic and physical properties are very similar. Short-period comets often have orbits typical of asteroids, and the orbits of some asteroids are identical to the cometary ones. In the course of physical evolution, which runs much faster for comets than for asteroids, a crust of high melting point forms at the surface of comets as a result of the progressive loss of volatiles under the action of the solar radiation. It prevents further evaporation of volatiles, and the comet becomes practically indistinguishable from an asteroid. Some asteroids show gas emission. Tedesco et al. [58] have proposed that asteroid 1580 Betulia is a faded comet. This conclusion was based on the study of its orbit and its unusual light curve which showed three maxima. Weissman et al. [57] composed a list of 29 possible comet-like asteroids. Among them there are several asteroids which have signs of binarity, such as 1580 Betulia and 2201 Oljoto. Observations demonstrate that some comets show evidence for double nuclei (31 cases are given in Ref. [59]) or an oblong, extended shape of the circumnuclear region, representing a stable system. Such cases are collected in Vsekhsvyatskii's monograph [60]. Tedesco et al. [58] pointed out that the light curve of the comet d'Arrest had three maxima. This and some other comets reveal such peculiarities which may be explained only from the point of view of multicomponent nuclei. The existence of comets and asteroids with two or more components is probably rather common and typical of small bodies in the Solar System [52]. Many asteroids or comets are able to keep clouds of satellites with a wide range of sizes (down to dust grains) in their gravitational fields.

3.2.3 Double craters

Practically all observed surfaces of planets, satellites and small bodies in the Solar System are covered by craters which have in general an impact nature. Long ago observers noted structures formed by pairs of craters which exist in abundance on the Moon and Mars. Such structures also exist on Earth. Voronov [61, 62] used probabilistic calculations (Monte Carlo method, Markov chains) to show that the actual number of double craters observed on the surfaces of planets and satellites exceeds the number that would be expected if they were assumed to be random. The hypothesis is that they may be formed by impact with systems (asteroids, comets) consisting of two fragments. This is the scenario discussed by Hut and Weissman [63]. Melosh and Stansberry [64], when considering the formation of the impact craters on Earth, came to the conclusion that 3 out of 28 craters with diameters more than 20 km are double. Some attempts have been made to explain their origin by different mechanisms, but the authors came to the conclusion that the most probable hypothesis is that the double craters on Earth result from the existence of a significant number of well-separated double asteroids among the celestial bodies approaching Earth.

3.3 Photometric studies of asteroids

3.3.1 Possibilities of modern photometry

Photometric observations of asteroids enabled one to obtain information on the periods of their brightness

variations which are interpreted as their spin periods, and also on the spatial orientation of their axes, the spin direction and their shapes, under the assumption that they are well described by triaxial ellipsoids. Catalogues of the photometric properties of asteroids [65–70] contain data on more than 500 objects.

Photometric observations provide the basis for developing methods for inverse problem solution in which the shape of a body is recovered from the field of scattered light. Such problems are very complex, and, as a rule, their solution may be found only if some a priori data are given. In this way, attempts have been made to obtain the shape of some asteroids, assuming them to be convex [71].

Kupriyanov [72, 73] has developed a method of solution of the inverse problem for nonconvex multicomponent solid bodies, which takes into account mutual shadowing of the components and multiple scattering of light reflected from their surfaces. Use of this method for investigations of asteroids complex in structure is probably quite promising.

A great majority of the observations of asteroids were obtained by electrophotometry based on the use of typical stellar electrophotometers which allow observation of only one object at a given time. Shifting the photometric data obtained during several consecutive nights along the time scale by a multiple of the period gives a so-called composite light curve. It describes the brightness variations of an asteroid during the period of its spin rotation. All photometric data presented as composite light curves are collected in several issues of the Asteroid Photometric Catalog [74].

The advance in techniques of astrophotometric observation led to the widespread use of high-sensitivity two-dimensional light detectors (in Russian astronomical literature they are usually called, not very accurately, panoramic light detectors). These detectors not only provide images of asteroid satellites but can also measure simultaneously the brightness of every object within a field of view, with a photometric error of a few hundredths of a stellar magnitude and allowing the detection of marginally faint objects. The diameter of the field of view is usually several arcminutes owing to the rather small linear dimensions of such detectors.

Use of modern electronic devices provides a good opportunity for the simultaneous measurement of asteroid brightness and brightness of one or several field stars, which is very valuable for asteroid studies. The asteroid brightness at a given moment may be determined by comparison with neighbouring stars. The method permits differential observations, which practically exclude the influence of the variations in atmospheric transparency during the night. High photometric precision and a great number of measurements allow one to detect tiny features of the light curves (see for example Ref. [75]), which might carry some information about the existence of a satellite of the asteroid. The higher the precision of the measurements, the smaller the changes of brightness that may be detected and hence the smaller the satellite that may be discovered from the photometric observations.

3.3.2 Photometric observations of double asteroids

The first evidence for the existence of double asteroids was obtained by Andre [76] from visual photometry of asteroid 433 Eros in February 1901, when a favorable opposition of Earth and the asteroid permitted the observation of eclipsing events. The light curve had two maxima with an amplitude of about 2 magnitudes and was very similar to that of double stars. Its analysis allowed Andre to determine a number of parameters of the binary system: the period of the asteroid's spin, 5 h 16.15 min; the size ratio of two ellipsoidal components, 3/2 or 1 (assuming their oblateness to be 1.2); the density, 2.4 g cm^{-3}; the eccentricity of the satellite's orbit, 0.569; the periastron longitude counting from the node line, 162°. The satellite's rotation period was estimated to be close to 7.7 h and the orbital semimajor axis to be 2.7 times the asteroid's radius.

In 1937, the famous variable star investigator Zessewitsch [77], while analysing observations of Eros published since 1901 and his own observations, discovered real regular variations of the asteroid's spin axis orientation, as well as a change of time interval between the primary and secondary maxima in the light curve. On the basis of these findings, he suggested that this asteroid was a binary. Beyer in Ref. [78] presents a list of the observed amplitudes of Eros's variability ranging from 0.2 magnitudes to 1.5 magnitudes. When in 1975 Eros passed at a distance of 26 million km from Earth, the amplitude of variation in brightness was 1.5 magnitudes [79]. To explain this fact, it was proposed that it had an exotic, dumbbell-like shape with longitudinal and transverse axes in the ratio 2.5 : 1 (25 km × 10 km) and the spin axis lying in its orbital plane.

The photoelectric observations of asteroid 624 Hektor obtained by Dunlap and Gehrels in Chile [80] also revealed a large amplitude of variability, reaching 1.2 magnitudes. An attempt to explain this by means of an irregular shape 100 km long and 2.5 times smaller across does not stand up to criticism. Cook was the first to reject the model of a trixial ellipsoid because of the small density, 1.5 g cm^{-3}, and suggested that this asteroid could be double [81]. Weidenschilling [82] proved that the elongated model was unstable and suggested a model of a contact binary asteroid: two components whose ellipsoidal form is caused by gravitational attraction. Based on this model the mean asteroid density was calculated to be 2.5 g cm^{-3}, which was in good agreement with the observations. Using the anomalous form of the light curves of the asteroids 49 Pales and 171 Ophelia, Tedesco [83] estimated orbital parameters of the satellites and obtained densities in the range 1.5–2.8 g cm^{-3}, typical for asteroids.

The great number of photometric observations which indicate the complex structure of asteroids, as well as the limited space for this review, give us no opportunity to describe all the results [84–86]. We will present some of them in the next section generalising photometric indicators of asteroid binarity.

The modern level of computer techniques and methods of frequency analysis can be used to look for hidden regularities in the brightness variations of the asteroid and for isolating periods of orbital motion and spin rotation of asteroids. The very first experiment in such studies revealed interesting results [87, 5]. The frequency analysis method applied to the photometric data and the results obtained for three particular asteroids are described in Section 4. Frequency analysis allowed the authors to find several periods for each of them, in addition to previously known periods interpreted earlier as rotational periods of a single body. The presence of multiperiodicity can be interpreted in terms of spin periods of the components.

3.3.3 Generalisation of the photometric criteria of multiplicity of asteroids

The success in photometric studies of asteroids, the large number of published light curves and attempts to distinguish photometric indications of the double structure of asteroids, made by a number of authors, as well as our own experience in studying double asteroids, allow us to generalise and complete the analysis of these indications. The photometry of asteroids provides astronomers with information about the period(s) of the brightness variations of the asteroids and about the field of solar radiation scattered by them, the development of which can be observed as a result of asteroid spin. The structure of this field appears in the shape and features of the asteroid's light curve.

1. The amplitude and the shape of the light curve give some indications of the binarity or more complex structure of the asteroid. At the end of the 1970s, Tedesco [83] noted that the light curves of asteroids 49 Pales and 171 Ophelia have practically flat maxima and Algol-like minima, characteristic of Algol-like eclipsing binaries. Based on these findings, he suggested that they were binaries and listed 10 other possibly binary asteroids. Calculations of equilibrium models for binary asteroids carried out in Italy in the middle of the 1980s [84] allowed evaluation of parameters of asteroid components from the amplitude of the light curve. Note that the maximum amplitude of the curve is used for such estimates, which is observed close to the moment of the intersection of Earth with the equatorial plane of the asteroid, i.e. under the condition that the amplitude increases at the expense of mutual eclipsing effects between the components. An amplitude greater than one stellar magnitude indicates possible binarity of the asteroid. The following signs of binarity were formulated by Cellino et al. [85] who determined parameters of binary systems for 10 large asteroids from the form of their light curves:

(a) Existence of a flat minimum in the light curve that indicated total eclipse. An example is the light curve of asteroid 192 Nausikaa (see Fig. 5) which has two flat minima.

(b) Strong variations of the light curve amplitude as a function of the phase angle under which the Sun illuminates the asteroid, caused by the mutual eclipsing effect, which depends on the phase.

(c) A significant change of the slope of the ascending and descending branches of the light curves from cycle to cycle, caused by the variable time of the beginning and the end of eclipse. Fig. 6 provides an example of two light curves for asteroid 87 Sylvia obtained with a time interval of two days. Both the amplitude and slopes of the ascending and descending parts of the light curve have changed, which

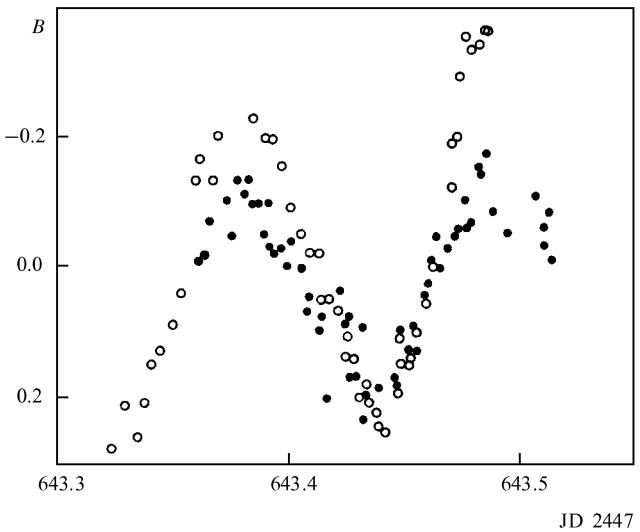

Figure 6. Light curves of asteroid 87 Sylvia obtained on 26 April (empty circles) and 28 April (filled circles), 1989, at the Crimean Astrophysical Observatory [96]. Alignment of the curves along the time axis is made by shifting the 28 April observations by an integer number of periods. The time measured in Julian days is plotted along the abscissa; relative stellar magnitudes are plotted along the ordinate.

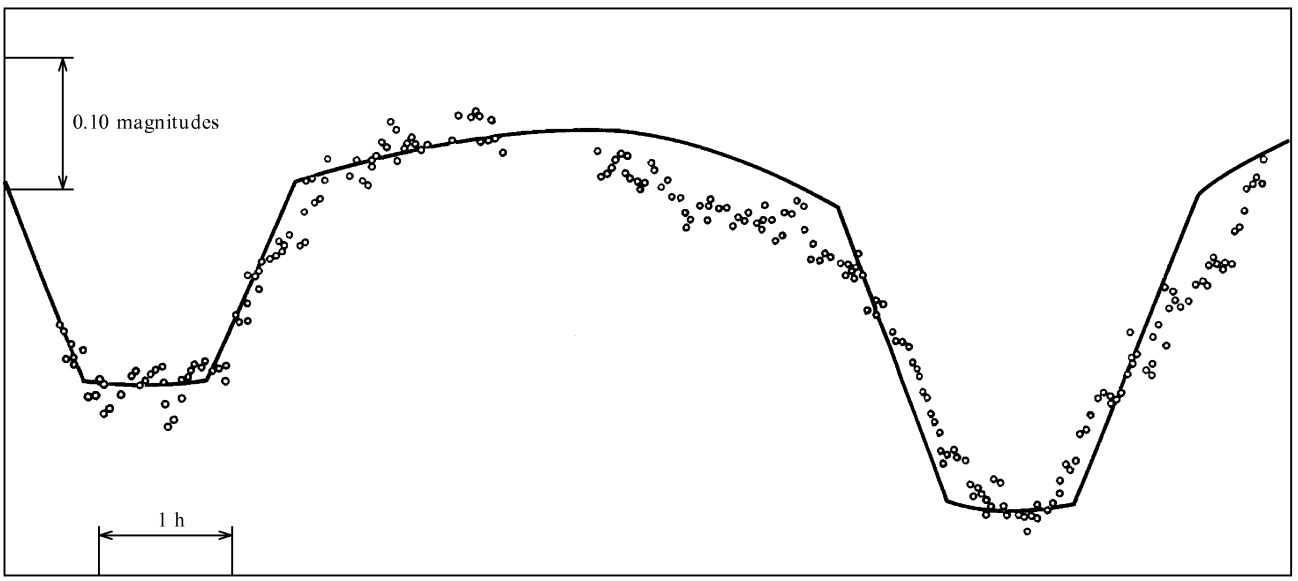

Figure 5. Light curve of asteroid 192 Nausikaa. Observations are shown by points; the curve shows a model calculation made in Ref. [85] assuming the asteroid to be double.

Table 1. Parameters of binary asteroids

Asteroid	Diameter/km	Satellite size/km	Satellite orbital radius/km	Ref.	Asteroid	Diameter/km	Satellite size/km	Satellite orbital radius/km	Ref.
2 Pallas	523	50	1000		216 Kleopatra	145	c. p.	cont.	[35]
			1400	[30]	243 Ida	54 × 24 × 21	1.5	100	[1, 47]
6 Hebe	192	20	—	[50]	423 Diotima	217	80	400	[115]
9 Metis	153	60	1100	[20]	433 Eros	35 × 16 × 7	20	60	[45, 76,
18 Melpomene	135	48	750	[54]	532 Herculina	230	46	1000	77]
44 Nisa	80	c. p.	cont.	[54]	624 Hektor	234	c. p.	cont.	[54]
49 Pales	140	50	450	[54]	1220 Crocus	24 × 22 × 12	12	50	[51, 54]
87 Sylvia	271	150	250	[96]	1580 Betulia	6 × 8	c. p.	cont.	[94]
146 Lucina	137	6	1600	[55]	4179 Toutatis	2.5	c. p.	cont.	[54]
171 Ophelia	90	30	300	[54]	4769 Castalia	1.7 × 1	c. p.	cont.	[91]
			160	[83]					[33, 37]

gives evidence for significant changes in the conditions of eclipse for the components.

(d) Presence of a wide maximum in comparison with sharp narrow minima. An example is also provided by the light curve of 192 Nausikaa shown in Fig. 5.

Changes in amplitude and shape of the light curve are most pronounced in the case of close binary asteroids which have components comparable in size. Observation or detection of a small satellite relative to the main component is hampered by the small probability of making observations exactly at the moment of eclipse and by the small amplitude of the eclipse in the light curve. Note also that the probability of detecting a remote satellite is also small since the eclipses would be short and could be observed only when the line of sight lies in the equatorial plane.

2. The determination of the rotational axis of an asteroid is made by using photometric observations with an accuracy of tens of degrees or better [67, 69]. The high precision in determining the pole coordinates allows one to detect their real changes, as was done by Zessewitsch for Eros [77], where there was reason to suspect the presence of a satellite causing precession of the asteroid's spin axis.

3. The value of the period, as has been pointed out many times by different authors, can be a sign of possible binarity of the asteroid. In 1983, Harris supposed that the main belt asteroids with periods more than two days could be binary systems [86]. It follows from the equilibrium model calculations made by Leone et al. [84] that those asteroids that show brightness variations with periods more than 6 h might be binary systems. Those showing periods between 5 and 6 h could be either binary or single rotating bodies. Thus, the value of the period can be considered as one indication of complex structure of the asteroid.

4. Presence of a multiperiodicity in the brightness variation of an asteroid can indicate a binary or more complex structure [87–94]. There should be more than two periods in the brightness variation, as a rule, since a single rotating body, in addition to the rotation period, can exhibit a so-called Euler rotation. Asteroids of complex structure show, as a rule, several periods: the orbital motion, the rotation of the components, the orbital precession as a whole, and, possibly, the rotation of the areas of the components. The rotational periods of the components can possess harmonics of different orders which appear as a result of the complex surface of the asteroid. Such a phenomenon is observed for rotating artificial Earth satellites and permits determination of the number of faces on their surfaces [95]. Note that for studying periodicities it is worth using not only one-colour photometric observations, but also colour index variation data which provide information on the change of colour with the rotational period of the asteroid's components [96].

3.3.4 Population of asteroids with satellites

The indications of asteroid multicomponent structure formulated above, on the one hand, and an abundance of observational evidence, on the other hand, enable us to consider the population of complex structure asteroids. Table 1 presents the data on those asteroids for which a number of binary system parameters have been obtained by one means or another. For the size of the asteroid, the diameter from catalogue [97] was taken in most cases; sizes taken from the original papers are also shown. For close pairs (c.p.) the size of the satellite is close to that of the asteroid. For contact systems (cont.), the satellite orbital radius is equal to the sum of the radii of the components. A more complete list of the asteroids suspected to be binary is given in Ref. [5]. It contains 51 members and is likely to include almost all the known representatives from this population.

It is worth noting that out of 500 studied carefully by different means (including photometry), this list contains about 10%. Nearly the same fraction, 6 binaries out of 69, is given by radiolocation (see above). Three out of 28 big craters on Earth are double [64]. In 1980, Chapman et al. [98] wrote that according to their estimates, 10% of large asteroids are binary. Thus, specific observations and further study of binary asteroids as a sufficiently numerous population of small celestial bodies should be fairly successful. However, one should bear in mind that the success of the observations will be determined not only by a successful choice of object, but also by its observability, i.e. by the orientation of the orbital plane of the satellite with respect to the observer.

4. Estimation of periods of asteroid components

Frequency analysis of the photometric observations enables one to reveal periodicities which are not obvious at first

glance, and to obtain information on periods caused by orbital revolution of the components of an asteroid which is complex in structure. This problem is related to a class of inverse photometric problems, where one tries to find some characteristics of the studied body by applying certain special techniques to the time series of asteroid brightness variations.

Photometric series of asteroid observations suitable for frequency analysis must contain a large number of individual measurements closely spaced in time. The time during which asteroids can be observed is restricted by their observability: usually, they can be observed close to opposition when the distance is a minimum and the brightness is a maximum. As a result, the phase angle determining the part of the disk illuminated by the Sun and the angle between the central meridian of the asteroid and the line of sight vary because of the asteroid's motion. The duration of the interval between observations that provides approximately constant conditions of asteroid observability is about two weeks for the main belt asteroids. When one is studying asteroids during a close approach to Earth these conditions must be considered separately for each case.

A feature of photometric series obtained by astrophysical observation is their discontinuity, caused by conditions of visibility of an object during the night, by weather conditions and by the allocation of observing time at the telescope. Therefore such series contain useful information over a short time interval, as a rule. Several methods for a sufficiently reliable analysis of such series with many gaps have been developed in astrophysics. They are described in detail in Terebizh's monograph [99] and are illustrated by numerous examples. Many years of experience of analysing such astrophysical time series and excellent scientific results show that the application of these methods for studying asteroids with complex composition is promising.

4.1 Method of frequency analysis of photometric data

Modern equipment provides good accuracy of measurements and high time resolution. These properties should be made use of for asteroid observations as far as possible. For this purpose it is appropriate to record simultaneously the brightness of the asteroid and of neighbouring stars in order to eliminate the effect of atmospheric extinction variations during the night. It is advisable to have at one's disposal a photometric calibration for all observations which uses an artificial photometric standard [100], to use absolute photometry and to determine the atmospheric extinction for each night of observations.

The frequency analysis should be performed for stellar magnitudes of the asteroid reduced to a unit distance from Sun and Earth and to a zero phase angle of solar illumination of the asteroid. The data must all be obtained in the same photometric system. The spectral band for such investigations can be chosen arbitrarily. It is best to use the band which provides a high signal-to-noise ratio. It should be noted that interesting results can be obtained by analysing the asteroid's colour indices. Therefore, photometry in two or more bands is needed. The ratio of the asteroid's brightness in two or more bands and its variation with time bear information about the distribution of patches over the surface of the asteroid or its comparison. The analysis of colours makes it possible to distinguish the orbital period, as the coloured spots on the components'

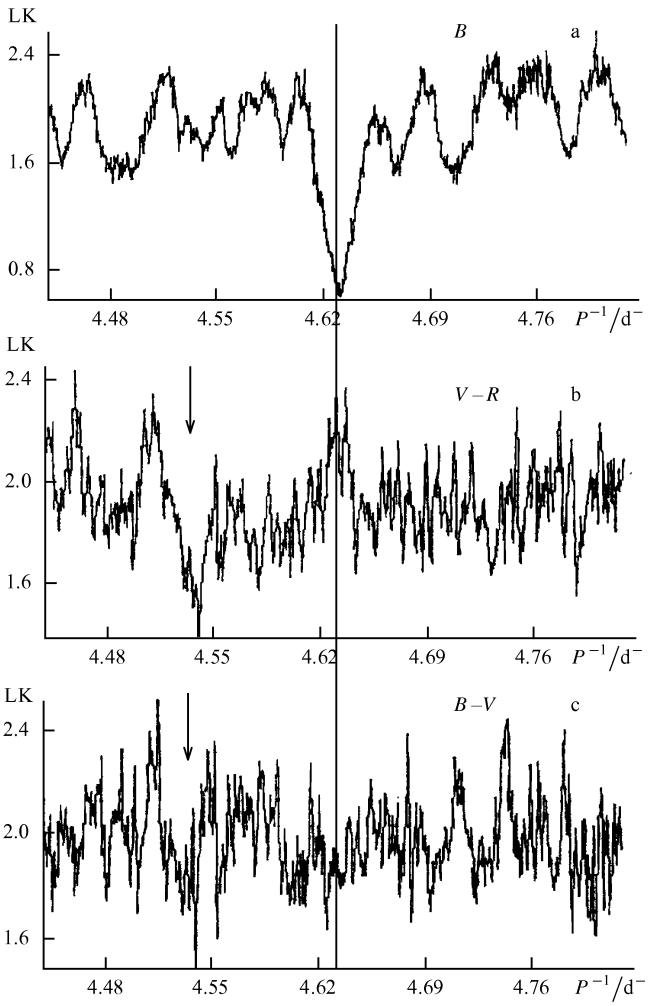

Figure 7. Periodograms obtained by the Lafler–Kinman method during frequency analysis of the asteroid's brightness in the B-band (a) and of the colour indices $V-R$ (b) and $B-V$ (c). The frequency measured in the number of periods per day is along the abscissa; the Lafler–Kinman parameter LK is shown along the ordinate.

surfaces exhibit only the spin periods of the components. This was the case for asteroid 87 Sylvia (see Fig. 7). The periodogram of the asteroid's brightness displays a sharp minimum at a frequency corresponding to the period 0.215985 d, and colour indices $V-R$ and $B-V$ show no periodic changes at this frequency. The colour variations revealed the presence of two periods which were interpreted in terms of the components' spin periods [96].

The search for brightness variation periods of variable stars has been carried out over more than one hundred years. The underlying principle of this search has been the construction of trial phase diagrams (light curves) with assumed periods and choice of the curve with the smallest dispersion. Currently, this search is made entirely by computer. One can distinguish two approaches towards the composition of the many codes for finding periods. One of them is based on the method of light curve construction with trial periods and on the development of automatic methods for isolation of the most probable period for which the dispersion of the points relative to the mean curve is a minimum. Different methods of analysis differ in the evaluation of the point dispersion, for example Lafler–Kinman's [101] and Yurkevich's [102] methods. Note that

the form of the light curve is not important for such analysis. These methods are applicable for analysis of series with large gaps, but for high reliability of correct period determination a large amount of data is needed. The second approach is connected with Fourier analysis. It is more rigorous mathematically but there are problems for discontinuous series analysis. In 1975, Deeming [103] published a method that eliminates frequencies modulated by gaps in the series of observations. This method assumes that the oscillations are sine waves and in the case of asteroids showing two-maxima light curves, it gives only the second harmonic of the real period.

Studies of characteristics of the motion of asteroid components were initiated by V V Prokof'eva [87–89] in the Crimean Astrophysical Observatory (CrAO). The results of studies for three asteroids are presented below. Two of them, 87 Sylvia and 423 Diotima, are large asteroids, for which the encounter probability, and, as a result, the likelihood of their disruption, are higher than for small asteroids [104, 105]. This could imply that they have complex structure. The third asteroid, 4179 Toutatis, belongs to a family of asteroids that comes close to Earth and may be an evolved binary system [106]. Its binarity was discovered by radiolocation at the beginning of December 1992 [38].

Observations of all three objects were performed on the digital television complex attached to the half-metre Maksutov meniscus telescope of the CrAO. The instrumental photometric system, similar to the *BV* system of Johnson–Morgan and the *R* system of Johnson [107] was provided by appropriate light filters. The method of photometric measurement of asteroid brightness is based on data reliability enhancement obtained by simultaneous use of two classical photometry methods: differential and fundamental [108]. Differentiality of the measurements was provided by the simultaneous measurement of the brightness of the asteroid and one of the neighbouring stars. Constant monitoring of an artificial photometric standard provided homogeneity of the data in the instrumental photometric system. Regular calibration of that system allowed the calculation of a reliable transition equation to the standard *BVR* colour system. In order to determine the atmospheric extinction during each night, specially chosen standard stars located close to the trajectory of the studied asteroid were observed. The usual time of exposure was 1–3 min for bright asteroids and reached 5–6 min for asteroid Toutatis. The accuracy of photometric brightness measurements varied from one to a few percent depending on the visual brightness and weather conditions. The transition to the standard photometric *BVR* system introduced no more than 3% error in asteroid absolute brightness.

The analysis of the photometric data was carried out with the use of numerical codes for searching for periods. The code 'Period', by which the majority of data were processed, was developed by Klepikov and modified by K V Prokof'eva. It uses simultaneously three different methods: those of Lafler–Kinman, Yurkevich and Deeming [101–103]. The code allows an efficient survey of the data folded with a given period, as well as selection of the polynomial power to fit slow brightness changes. Then the polynomial can be subtracted from the corresponding photometric data, thus removing known periods, which is necessary for finding hidden periodicities [99]. When multiple periods were present, the data cleaning, as a rule, was made consecutively for periodic oscillations with decreasing amplitude.

Astronomical observations with large gaps are well known to complicate the power spectrum of the corresponding objects. This phenomenon is called frequency substitution [99]. The frequencies produced as a result of interaction of the true frequency with the data gap frequencies, caused by time discontinuity of the observational data, are known as conjugate frequencies. Sometimes, these false frequencies are called artifacts. The amplitudes of the peaks corresponding to these frequencies are comparable with the peaks corresponding to the true frequency. So-called combination frequencies which arise as a result of the transition of the signal through a nonlinear medium are observed in the power spectrum as well [109]. They represent the sum of and the difference between the main frequency of the signal and the proper frequency of the medium. In astrophysical data, the discontinuity of the series under examination can be treated as such a medium. It has frequencies determined by the observational conditions, the length of the series or its segments, the series discontinuities over intervals of a day or month and by other causes. Note that if there is some a priori information, for example the presence of two maxima in the asteroid's light curve, this can be used to justify one or another of the periods revealed by the frequency analysis.

To reveal real asteroid brightness variations, a set of indicators was used. The discovered frequency was considered real if:

— the power spectrum showed the presence of harmonics and frequencies of multiple periods, as well as of the combination frequencies symmetrical to that studied;

— phase diagrams (light curves) constructed with the studied period had no gaps caused by the discontinuity of the observations and showed the presence of two maxima and two minima of approximately equal amplitude;

— phases of the light curves constructed from different series of observations were in agreement;

— periodograms of a model obtained by substitution of random numbers for stellar magnitudes in the studied series showed no peculiarities near the frequency taken to be true;

— the peak corresponding to the frequency of the discovered period was seen in periodograms obtained by different methods.

4.2 Close binary system 87 Sylvia

The amplitude of brightness variations for asteroid 87 Sylvia varies in the range 0.30 to 0.62 magnitudes [65]. The analysis of data published in the literature showed that the maximum difference in the amplitudes is observed when the direction to the observer lies close to the asteroid's equatorial plane so that eclipsing effects can appear. The CrAO observations were obtained under just such conditions. From 26 April to 11 May, 1989, *B*-observations were carried out during 6 nights, and during 4 nights simultaneous *BVR* and integral light observations were carried out. In total, about 240 brightness measurements in the *B*-band and 130 measurements of the $B-V$ and $V-R$ colours were used for the frequency analysis. The search for periodicities was performed for different series of

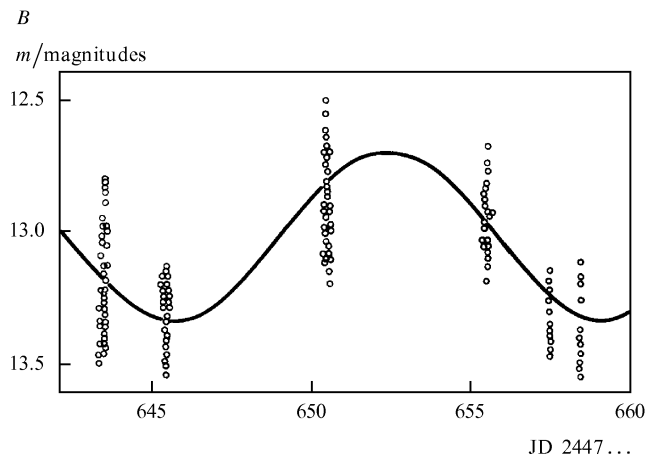

Figure 8. Change of absolute B-brightness of asteroid 87 Sylvia as a function of time measured in Julian days. The curve represents a sinusoid with period 13.5 d.

observations, which enhanced the probability of obtaining the true periods.

Absolute variations in the B-band of the asteroid were detected [87] which can be approximated by a sinusoid with a period of about 13.5 d (see Fig. 8). Two maxima and minima imply a total period of ~ 27 d. The accuracy is about several days and in order to confirm its correctness, frequency analysis of the published values of the absolute brightness of the asteroid was carried out and revealed two close periods of 29.1 and 32.1 d [110]. It was assumed that such variations of the asteroid's brightness with an amplitude of a few tenths of a stellar magnitude could be explained by precession effects.

Subtracting the sinusoid with period 13.5 d from the observational data removed the night-to-night asteroid brightness variations. Analysis of the cleaned data array showed clearly the presence of a deep minimum in the Lafler–Kinman periodogram, shown in the upper panel of Fig. 7. The frequency of the minimum corresponds to the known value of the asteroid's spin period, 0.215985 d. There are three minima symmetric to the main frequency; they are marked by arrows and correspond to combination frequencies: the sum and difference of the main frequency, those corresponding to periods 27, 13.5 and 6.7 d, and the discontinuity of the observations. The data folded with the period found are shown in Fig. 9. A 10th order polynomial fits the mean light curve quite well. The dispersion of separate points near the curve is significantly higher than the observational errors, which points to the possible existence of other periods and gives reason for further frequency analysis. Before doing this, data rectification with respect to this period was undertaken.

The frequency analysis of the twice cleaned data showed that the set of indicators of a true period is satisfied for two periods: 0.221 and 0.211 d, corresponding to frequencies 4.53 d^{-1} and 4.74 d^{-1}, respectively, with a difference between them of about 0.2 d^{-1}, which corresponds to the period of gaps in the observations of about 5 d. The periodograms obtained in the vicinity of these frequencies

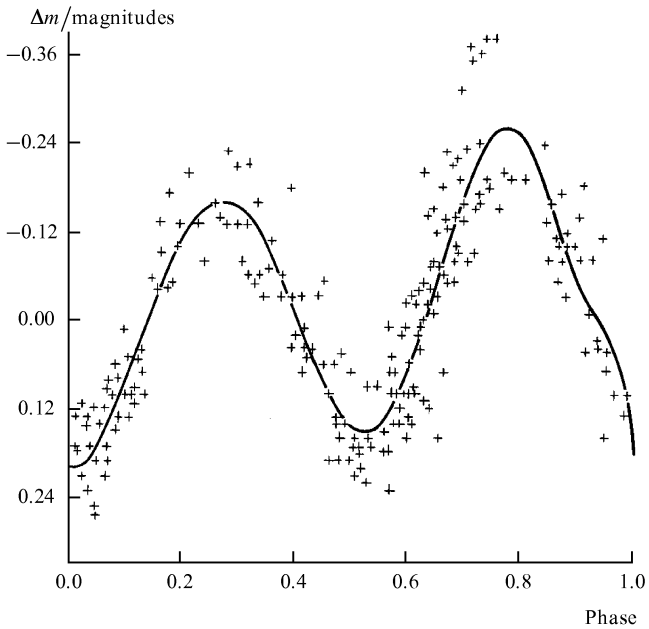

Figure 9. Light curve of asteroid 87 Sylvia folded with period 0.215985 d for B-observations after removal of the frequency corresponding to the 13.5 d period. The zero phase is taken at the moment 1989 April 26.324 JD. The curve represents a tenth order polynomial.

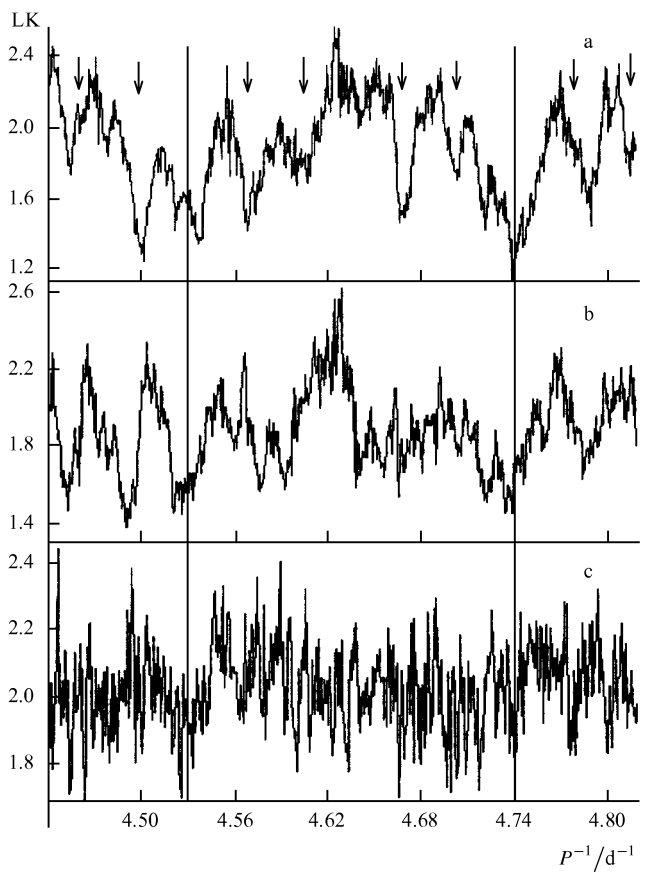

Figure 10. The Lafler–Kinman periodograms obtained (see Fig. 7) for two series (a) and (b) of the observations of asteroid 87 Sylvia after double cleaning of the frequencies corresponding to periods 13.5 d and 0.215985 d. The vertical lines show the detected frequency positions 4.53 d^{-1} and 4.74 d^{-1}; the arrows mark combination frequencies. The result of analysis of modelling the asteroid brightness variations by random numbers is presented in (c).

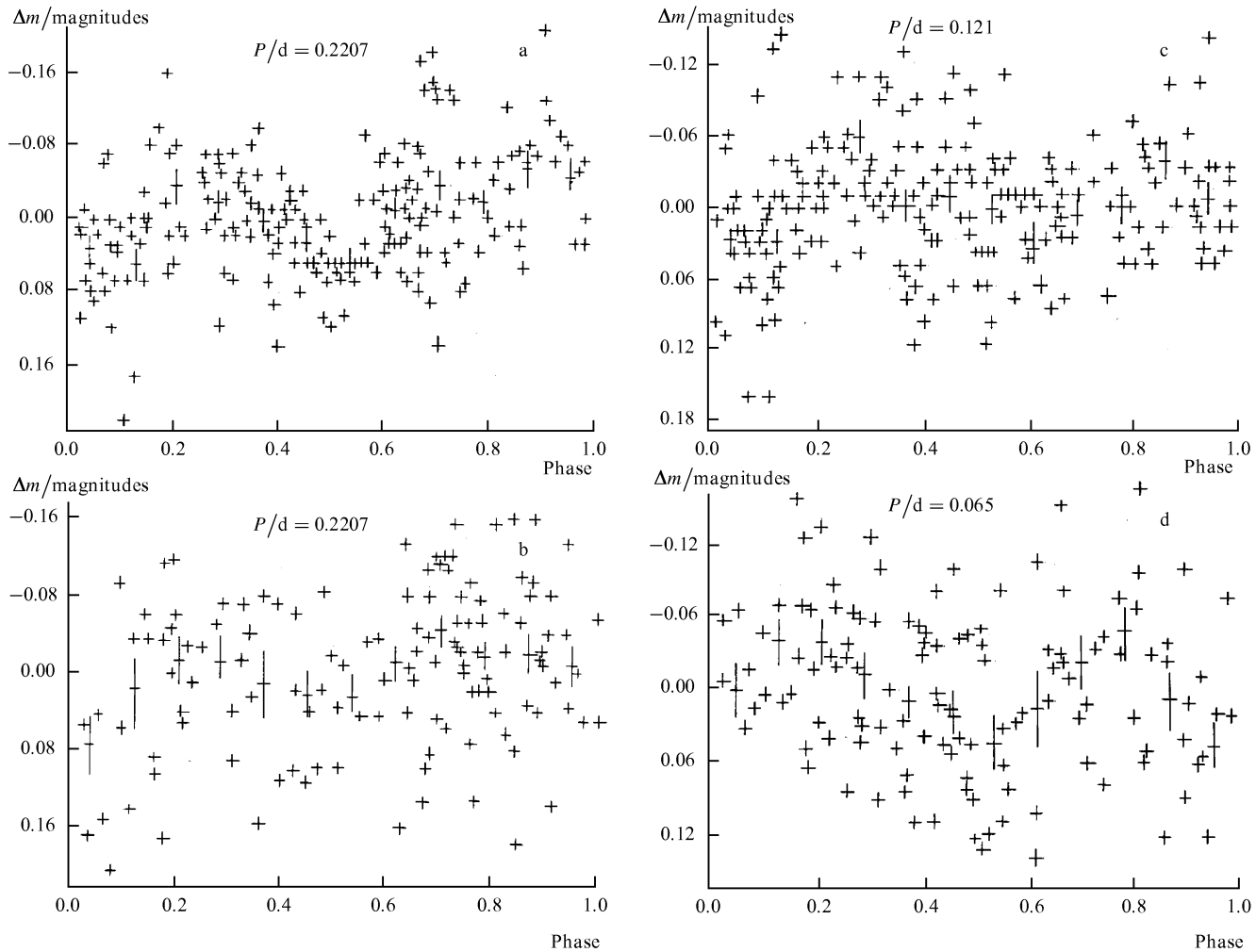

Figure 11. Phase diagrams demonstrating rotation of the first component of asteroid 87 Sylvia and constructed by using its B-magnitudes (a) and $V-R$ colours (b) with the period 0.2207 d; rotation of the secondary component is seen from the phase diagrams constructed by B-magnitudes with the period 0.1207 d (c) and $B-V$ colours with the period 0.065 d (d). The vertical bars represent the mean values inside bins and their errors.

from two series of observations are shown in Fig. 10a and Fig. 10b. The vertical lines mark the new frequencies; the arrows show the combination frequencies located symmetrically which represent the sum and difference of these oscillation frequencies with frequencies corresponding to the periods 27 and 13.5 d. For comparison, Fig. 10c shows the periodogram for a model consisting of random numbers substituted for the stellar magnitudes, keeping the real moments of observation unchanged. Only use of the results of frequency analysis of the asteroid's colour indices, $B-V$ and $V-R$ (see Fig. 7), made it possible to select the first of these two periods and to identify its value, 0.2207 d. The light and $V-R$ colour index curves obtained with this period are shown in Fig. 11a and Fig. 11b.

Analysis of the data performed after triple cleaning of the photometrical series for this asteroid revealed the presence of a period of 0.12 d (see Fig. 11c). Analysis of colour observations confirmed a periodicity at high frequencies. This periodicity was most clearly exhibited in the $B-V$ colour index variations. By analogy with usual two-maxima light curves, V V Prokof'eva and Demchik [96] argued that the colour light curve may also display two maxima. In that case the period turns out to be equal to 0.065 d (Fig. 11d). Within the uncertainty, this period is the second harmonic of the period 0.12 d found in the colour variations. Note that if the second component has four colour spots instead of two, the frequency analysis of the brightness and colour variations gives similar results.

Having obtained evidence for asteroid binarity from the frequency analysis, one can evaluate some of the parameters using the calculations of equilibrium models of binary asteroids of Leone et al. [84]. Assuming the maximum amplitude of the variability to be 0.65 magnitudes, from the known period 0.215985 d we can estimate the components' mass ratio, $M_2/M_1 = 0.3-0.1$ and their mean density, 4.5 g cm^{-3}. One can evaluate the ratio of the components' effective radii, $R_2/R_1 = 0.7$, by supposing their disks to be round. If this is the case, the components' brightness differs by about 0.8 magnitudes. Knowing the asteroid's diameter, 271 km, estimated by assuming it to be a single body, we obtain for the effective diameters of the components $R_1 = 227$ km and $R_2 = 150$ km. Under the assumption of synchronous orbit of the satellite, one can estimate its radius to be 250 km, with a distance between the components' surfaces of only about 60 km. Thus, asteroid 87 Sylvia is a close binary system.

4.3 Binarity of asteroid 423 Diotima

The spin period of asteroid 423 Diotima, 4.622 h, catalogued in Ref. [65] was found in three series of observations with durations of 7, 5, and 6 h. On 10 August, 1981, the observations were obtained in Chile [111] and showed the presence of two maxima and one minimum over 7 h of observation. The amplitude was 0.06 magnitudes with the brightness difference in the maxima being 0.02 magnitudes. On 10 November 1982, a 5 h run revealed the presence of two maxima and one minimum. Schober notes that these maxima were separated by 2.5 h in 1982 and 4.5 h in 1981. In addition, in 1982 a sharp deep (0.1 magnitude) minimum lasting for about one hour was recorded, whereas in 1981 the light curve form was close to sinusoidal. On the basis of these features, Schober assumed the existence of a satellite. During observations made in Italy on 22 November 1982, lasting 6 h, two maxima and two minima were recorded [112] with an amplitude of 0.18 magnitudes. Two groups of authors came to the conclusion that the asteroid's light curve was irregular and ambiguous, which complicated the period determination. Nevertheless, they presented the value 4.622 h [113].

In the Crimean Astrophysical Observatory, 920 V-photometric measurements of asteroid 423 Diotima were obtained during 7 nights [90, 114]. The total duration of the asteroid brightness measurement was 41.6 h. An additional control for the correctness of the asteroid absolute brightness determination was provided. For this purpose, special observations of stars whose brightness was recorded simultaneously with that of the asteroid were made.

The entire series of observations is presented in Fig. 12. The amplitude of the asteroid brightness variations during individual nights is about 0.2–0.3 magnitudes, and a possibly regular variability over an interval of a few days is significantly higher. Similar brightness variations observed for asteroid 1220 Crocus were explained by forced precession induced by a satellite [94]. V V Prokof'eva et al. [90] argued that the brightness changes of asteroid Diotima with an amplitude of 0.8 magnitudes may give evidence for the existence of a satellite.

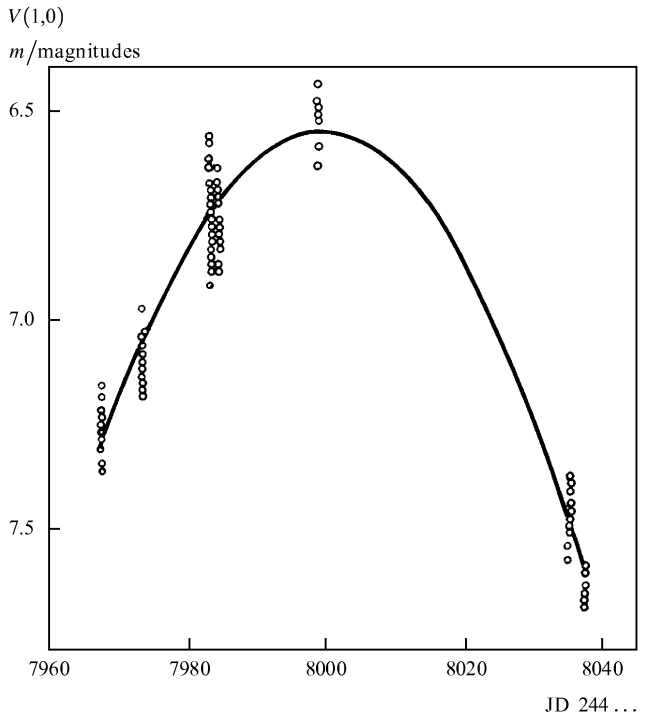

Figure 12. Change of absolute magnitude $V(1,0)$ of asteroid 423 Diotima as a function of time in Julian days. The curve is a third order polynomial.

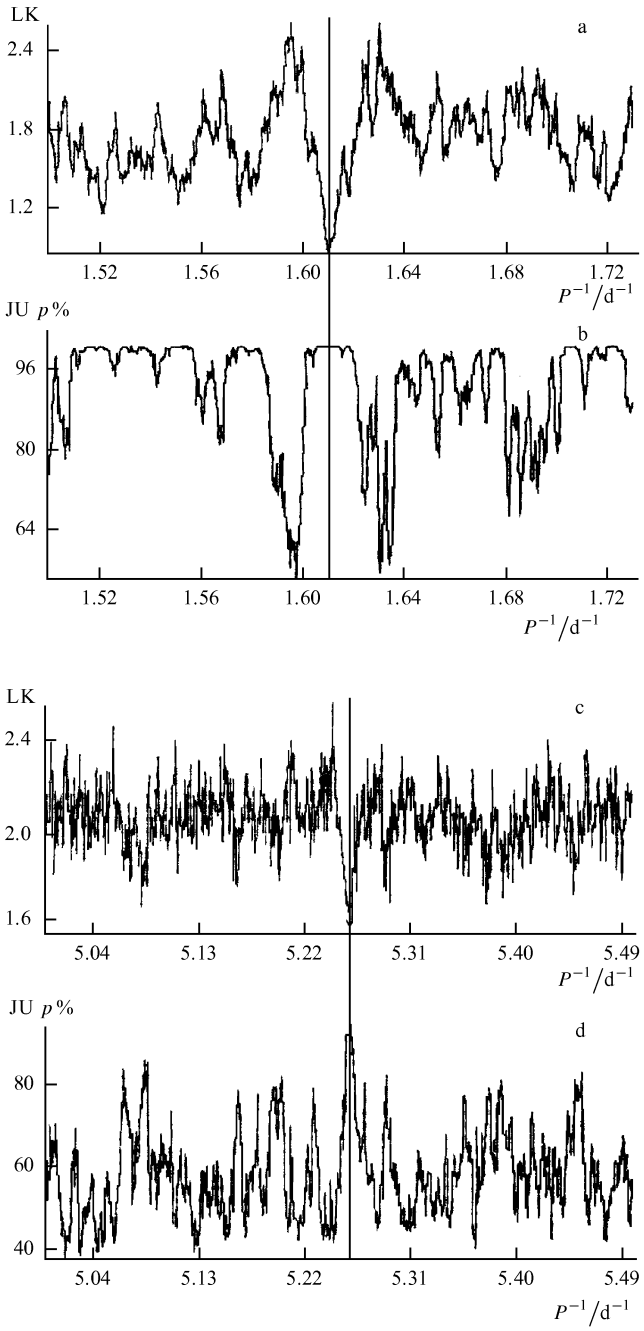

Figure 13. The Lafler–Kinman (a, c) and Yurkevich (b, d) periodograms constructed for single (a, b) and twice (c, d) cleaned series of observations. The vertical lines indicate the frequencies corresponding to the periods 0.621 d and 0.190 d. Frequency is along the abscissa; the Lafler–Kinman parameter LK (a, c) and the probability of the existence of the given frequency (b, d) are along the ordinate.

Frequency analysis of data, obtained after slow brightness variations have been fitted by a polynomial and subtracted from the photometric data, detected a period of 0.621 d at a high significance level (see Figs 13a and 13b). The light curve obtained with this period is shown in

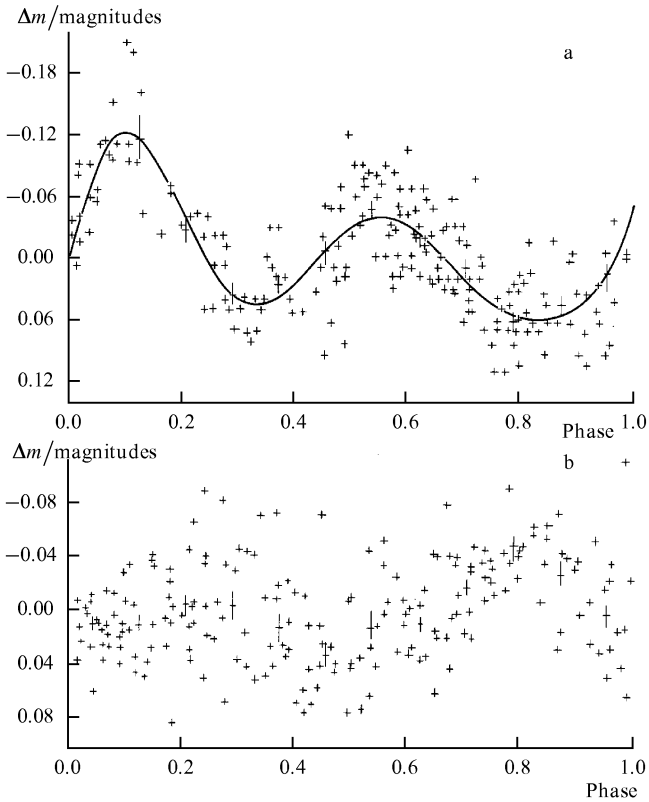

Figure 14. Light curves of asteroid 423 Diotima constructed with the periods 0.621 d (a) and 0.190 d (b). The curve is a sixth order polynomial; the points with vertical bars show the mean brightness inside the bin and its rms error.

Fig. 14a. It exhibits two maxima of different amplitude, with the highest having a sharp form. The maximum amplitude is about 0.2 magnitudes and the maxima differ by 0.09 magnitudes. Note that short time series of observations, which had been used earlier to determine the spin period of the asteroid, did not allow this period to be discovered.

Removing the oscillations with period 0.621 d from the observational data was done by subtracting a polynomial (see Fig. 14a). The Lafler–Kinman and Yurkevich periodograms are shown in Fig. 13c and Fig. 13d. The light curve obtained using the period 0.190 d is presented in Fig. 14b. The amplitude of brightness changes is about 0.08 magnitudes; the maxima differ by 0.04 magnitudes.

Frequency analysis of dense series of photometric observations for asteroid 423 Diotima revealed the presence of three brightness oscillations. The longest period has been determined very roughly and is about 200 d. Its amplitude is near 0.8 magnitudes and its smooth brightness variations suggest that it is real. A source of such oscillations could be a satellite-induced precession. Two other periods, 0.621 d and 0.190 d, according to assumptions by Prokof'eva and Karachkina [90, 114], are spin periods of the asteroid's components. If the orbital period is accepted to be 0.621 d, the orbital radius is found to be 400 km. The photometric data suggest the components measure 200 km and 80 km across.

4.4 Two-component structure of asteroid 4179 Toutatis

Asteroid 4179 Toutatis belongs to a group of asteroids which undergo close encounters with Earth. In 1992–1993, extensive studies of this object were made while it passed Earth at a distance of 3.6 million km. Radiolocation [38] revealed it to consist of two fragments. By using photometric and polarimetric observations, Kruglyi e-t al. [115] and Vasil'ev et al. [116, 117] have evaluated its diameter as 2.5–2.7 km assuming it to be a single body. Photometric observations of Toutatis have been performed in many observatories around the world [118].

A preliminary frequency analysis of Toutatis' brightness has been made using V-observations obtained in CrAO [93]. The analysis was done in the period range of less than one day and revealed the presence of a few frequencies, which indicated that the asteroid was binary. A more detailed analysis in a wide frequency range has been performed using unified Crimean and Kharkov observations [91]. All the data were reduced to a unique photometric system, V, as well as to unit distances from Sun and Earth and to zero phase angle. To increase the reliability of the results, different averaging of the data was made yielding several series with different time resolution. Each of them has been analysed in the intrinsically optimal frequency region. Overlapping of the frequency range ensured doubling of the results obtained. The main series consisted of 314 brightness values with an accuracy better than 0.01 magnitudes and a time resolution of 10–30 min. The problem turned out to be rather complicated as many diverse periods were found. Frequencies of the periods found were cleaned from the data, with the oscillations being removed in turn of decreasing amplitude. Many harmonics were discovered; however, the main periods were successfully distinguished (Fig. 15).

The period 7.48 d has an amplitude of about 1.0 magnitudes and yields the light curve with two minima. The first moment of the deepest minimum observed by us at JD = 2448983.523 is displaced by an integer number of periods from the moment when, according to radiolocation [39], the asteroid's component crossed the line between the asteroid and the locator, with the larger component closer to the observer. This is an argument which suggests that the period found is the orbital period.

The period 62 d is determined rather roughly, as it is comparable with the duration of the observations. It might be connected with the orbital axis precession.

The periods 2.85 and 1.66 d were suggested by V V Prokof'eva et al. [119] to be the components' spin periods. This is in accordance with radiolocation data, showing small spin velocities of the asteroid as a whole and of its components separately, which were obtained with a small echo-signal width of 2 Hz. The number of harmonics, 10 and 7, indicate a complex surface structure of the asteroid's components, which possibly have a lot of fractures, spots and other details. As the asteroid rotates, they produce a high-frequency modulation and hence cause the harmonics.

Analysis in a high frequency range allowed a more sophisticated examination of the data, which were grouped by maximum and minimum asteroid brightness varying with the period 7.48 d. This made it possible to connect the periods with individual components. The period 2.85 d was suggested as the spin period of the larger component [119]. The period 1.66 d is likely to relate to the secondary, smaller, component which might be fully or partially eclipsed by the first during the deepest minima.

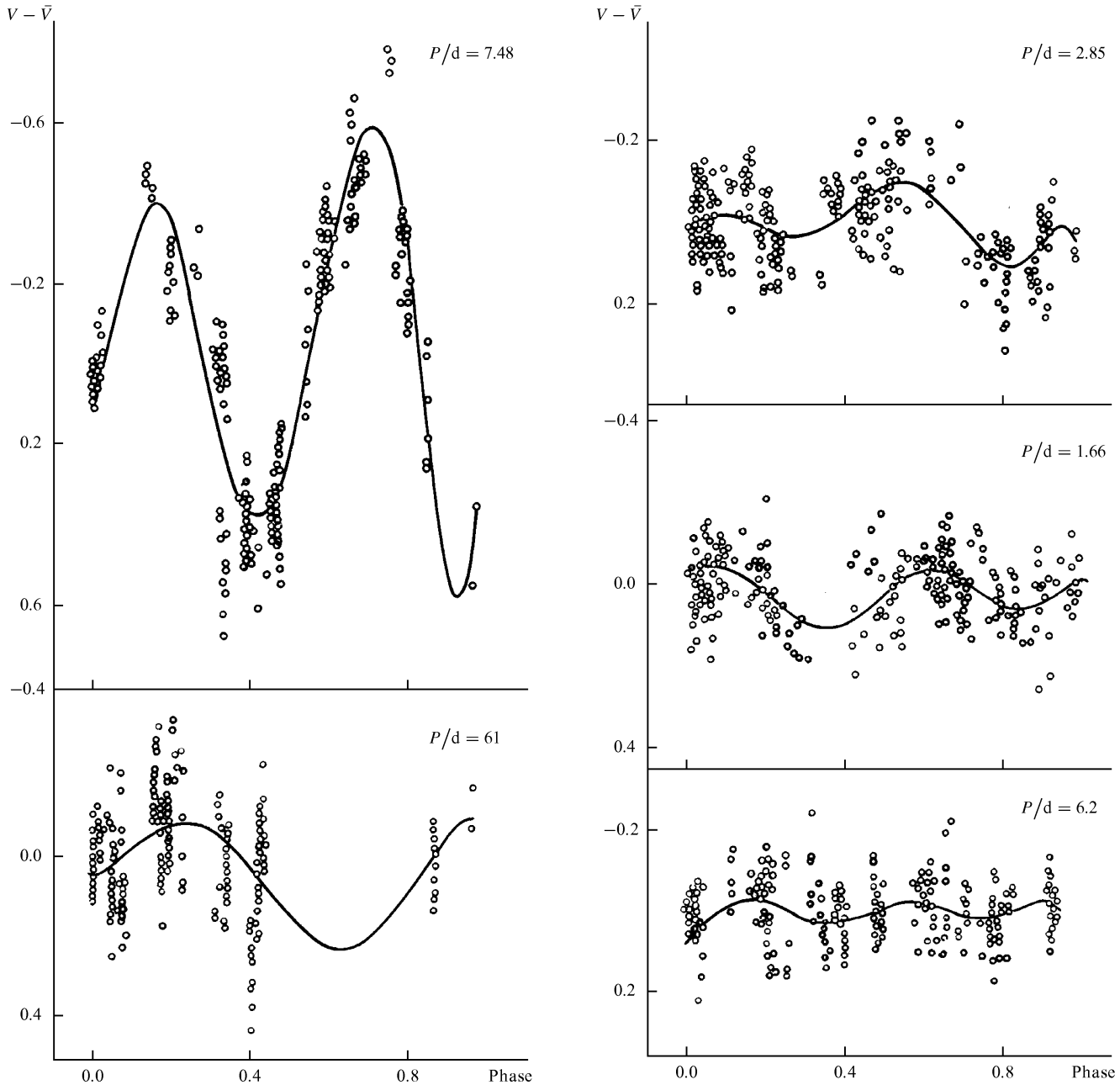

Figure 15. Light curves of asteroid 4179 Toutatis constructed with the periods found shown in the plots.

The ratio of the components' rotational periods, P_1/P_2, and the echo-signal width for each component, B_1/B_2, enable us to evaluate their diameter ratio, D_1/D_2. It is well known [44, 120] that

$$B = \frac{4\pi D \cos\delta}{\lambda P}\,, \tag{1}$$

where λ is the wavelength used for location, δ is the asteroidocentric declination of the locator which may be taken to be the same for both components. From expression (1) we obtain the ratio of the components' diameters, $D_1/D_2 = B_1P_1/B_2P_2$. The ratio $B_1/B_2 = 0.64$ was found from radiolocation images of the asteroid shown in Fig. 3 taking into account that the upper component is closer to the locator. The ratio of the periods, $P_1/P_2 = 1.71$, gives the ratio of the diameters, $D_1/D_2 = 1.1$. This agrees with the estimates of Zaitsev e-t al. [120] according to which the ratio of cross sections of the components measured on 9 November was 0.85 and, hence, $D_1/D_2 = 1.09$.

Frequency analysis of the variability in brightness of asteroid Toutatis revealed that it was likely to consist of two components. Comparison of the optical and radio data points indicated an orbital period of 7.48 d. The period 62 d might be caused by precession of the orbital motion. It was also assumed that the spin periods of the larger and smaller components are 2.85 and 1.66 d, respectively. The components must have an angular form, fractures and inhomogeneous surfaces.

5. Origin and dynamics of double asteroids and asteroid satellites

In this section we will consider current models for the origin of satellite systems, and study the problem of stability of asteroid satellites and how they might have formed.

5.1 Cosmogonical models: a possible change of theoretical paradigm

What is the place of asteroids in the modern picture of the formation of the Solar System? The hypothesis of Olbers, who discovered Pallas and Vesta, that the asteroids are fragments of an exploded planet, is presently denied. From the point of view of modern cosmogony, asteroids are building material for a planet whose construction was interrupted by the perturbing action of Jupiter. This interaction induced a characteristic encounter velocity of up to 5 km s^{-1} inside the asteroid belt, and escape velocities from the surfaces of asteroids are at least 10 times lower: for the largest asteroid, Ceres, measuring 1000 km across, the escape velocity is about 0.5 km s^{-1}. Note that the typical chaotic velocity of bodies inside a planet formation zone is nearly equal to the escape velocity for the largest of the bodies from the zone, or for the planet embryo [121], which permits the planetesimals to unite during inelastic encounters.

As is pointed out in Ref. [121], the factor of ten 'heating' of the asteroid belt not only prohibits accretion-induced coalescence of asteroids during mutual encounters, but also leads to an intensive encounter-induced disruption of asteroids.

Thus, according to generally accepted views, in the Solar System there are 9 'true' planets which have developed satellite systems as a rule, and many asteroids which are just 'broken bricks' in the place of a planet which never formed and hence cannot pretend to the normal status of planet. This implies an absence of satellites, which are usually present near all large planets.

The discovery of Ida's satellite placed asteroids immediately in the same league as other planets, at least in having satellite systems. Therefore, the probability of the existence of satellites near asteroids should be evaluated from the point of view of a general theory of satellite system formation. Unfortunately, no such theory exists as yet, which complicates our task. On the other hand, the asteroids' binarity itself must help us in developing a detailed theory of satellite formation.

Let us trace the evolution of satellite formation models. Before 1978, it was accepted that three out of five planets from the Earth group — Mercury, Venus and Pluto — had no satellites. Two very small satellites are known to orbit Mars (the mass ratio of Phobos and Deimos to Mars is about 10^{-8}). Only Earth, with its very large satellite, the Moon (1/81 of the planet's mass), looked like a clear anomaly.

The masses of the satellite systems are about 0.021–0.025% of the planet's mass for Jupiter, Saturn and Neptune, and only 0.01% for Uranus. One could conclude that the smaller the planet, the smaller the mass (both absolute and relative) of its satellite, with the only exception being the Earth–Moon system. This uniqueness of the Moon provoked the hypothesis that it was formed as a result of a catastrophic event — a tangential megaimpact [122, 123]; an enormous body similar to Mars in size strikes Earth on a tangential trajectory, tears out a piece of the mantle and flies away (where? — unknown). Part of the displaced matter forms a massive disk from which the Moon subsequently forms.

Satellites of the giant planets are subdivided into two classes: regular satellites located near the planet's equatorial plane on approximately circular orbits, and irregular ones with a retrograde rotation (relative to the intrinsic rotation of the planet) or just with large eccentricity and orbital inclination. According to the Shmidt–Safronov model [121, 124–126], regular satellites were formed from a protosatellite disk as a result of the coalescence of tiny particles. Another formation mechanism is usually invoked for irregular satellites of giant planets: capture of a 'ready-made' large body of satellite size from a heliocentric orbit [127–130]. However, this hypothesis cannot fully explain the diversity of irregular satellites with only one capturing mechanism [131]. Moreover, the large mass of the retrograde Triton makes its capture extremely improbable. It is worth noting the hypothesis according to which Pluto used to be a satellite of Neptune [132]. Thus Pluto, like the asteroids, is in fact deprived of 'genuine' planet status. Ruskol [125] considered the accretion mechanism for the formation of the Moon. However, in Ref. [133] it is asserted that accretion models cannot explain the origin of such a massive body as the Moon.

Thus, until the end of the 1970s three theories of satellite formation coexisted peacefully: for regular satellites — the accretion model; for irregular satellites — the capture model; for the Moon — a megaimpact model. According to the accretion model, satellite formation is a regular process and the satellite's characteristics reflect the properties of a protosatellite disk. The models of capture and megaimpact are based on accounting for random and low-probability events. The last model has a large number of free parameters, which can be adjusted to give any scenario desired. Catastrophe is a panacea that can be used to solve all cosmogonical problems by brute force. In that case the dynamic properties of satellite systems result by chance and do not depend on the formation conditions. The theory of 'catastrophism' was seriously damaged by Christi's discovery of Charon, an enormous satellite of Pluto with a mass of 15% of the planet's mass. This does not permit further consideration of Pluto as a former satellite of Neptune: even if one imagines a double satellite, how one could detach it from the planet without disruption? Thus Pluto confirmed its status as a genuine planet, and the hypothesis of megaimpact should now be extended to the large moon Charon. This decreases significantly the plausibility of such a model. The problems increased after numerous reports on the discovery of binary asteroids appeared. In order to explain these bodies, the megaimpact model had to be applied again, which exhausted it completely. Strong damage to catastrophism was caused by the Galileo spacecraft which discovered a satellite near the second asteroid it studied. Obviously, asteroids with satellites are far too numerous for the model of low-probability, carefully calculated tangential megaimpacts. Does it mean that for asteroid satellites to be explained one needs to find one more, a fourth class of cosmogonical models? We believe that the method of constructing a unified model for all types of satellite systems is more promising. Below we will consider the stability of prograde and retrograde

satellite orbits, and then will sketch an accretion model that explains satellite formation both around main planets and around asteroids from the same standpoint.

5.2 Stability of satellite orbits

Where may and where may not planetary satellites move? Traditionally, the region of satellite motion is considered to lie within a Hill's sphere with a radius equal to the distance to the Lagrangian point L_1 [134]

$$R_{\mathrm{h}} = R\left(A - \frac{A^2}{3} - \frac{A^3}{9}\right)^{1/3}, \qquad (2)$$

where $A = (m/3M)^{1/3}$, m is the planet's mass, M is the mass of Sun, R is the radius of the planet's orbit. However, firstly, it has been recognised that the stability depends on the direction of revolution: the retrograde satellites are more stable than the prograde ones [131, 135–139]. Orbits of the prograde satellites (which revolve in the orbital direction of the planet) lose their stability by approaching the Hill's sphere boundary; the retrograde satellite may exist in a stable configuration beyond the Hill's sphere, although in a very limited area [131].

Let us present, following Ref. [131], the results of analysis of satellite particle motion with prograde or retrograde revolution around a planet or an asteroid in the planet's orbital plane taking into account the Sun's influence (plane restricted 3-body problem). The orbit of the planetary body is assumed to be circular, and the coordinate frame is rotating with the planet. Fig. 16 shows the results of calculations for Jupiter. The boundary $X = 0.06$ beyond which the likelihood of satellite existence is practically zero is close to the Hill's sphere, $R_{\mathrm{h}} = 0.0667R$ [Eqn (2)].

Thus, according to Eqn (2) and numerical calculations [131, 138, 139], any asteroid is surrounded by a zone where it successfully controls its satellite's motion and its gravitational field dominates over the Sun's attraction. Let us evaluate, using Eqn (2), the maximum radius of the satellite's orbit for asteroids from the main belt and those which approach the Earth:

$$R_{\mathrm{h}} = 545R_{\mathrm{a}}\,(R = 2.7\,\mathrm{AU}) = 202R_{\mathrm{a}}\,(R = 1.0\,\mathrm{AU})\,, \qquad (3)$$

where R_{a} is the radius of an asteroid with a density of 3.5 g cm^{-3}.

Let us address the question about the nature of satellite motion inside the Hill's sphere. In Fig. 16 the regions of stationary orbits (not changing in time in the rotating frame) appear as thin lines:

1. Circular orbits with prograde rotation (D) which extend up to 0.4 of the radius of the Hill's sphere. This value varies from $0.37R_{\mathrm{h}}$ for Jupiter [131] to $0.42R_{\mathrm{h}}$ for small asteroids [140].

2. Egg-like orbits with prograde rotation elongated outward (N) or toward (S) the Sun.

3. Orbits with retrograde rotation (R), which differ from those in the D-class only in the direction of rotation and extend far beyond the Hill's sphere. At large distances from the planet the R-orbits turn into epicyclic ones.

Thus, inside the Hill's sphere an inner zone measuring $0.4R_{\mathrm{h}}$ can be distinguished, where the satellites with prograde rotation can move along circular D-orbits for an infinitely long time [131]. In the outer zone of the Hill's sphere the prograde satellites move along elliptical orbits

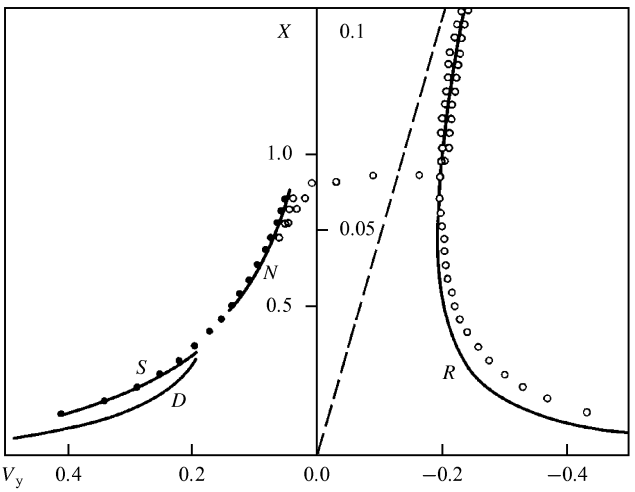

Figure 16. Area of initial coordinates and velocities of test Jovian satellite particles. The particles are placed along the X-axis continuing the Jupiter – Sun line (figures to the right are distances between Jupiter and the Sun, to the left the Hill's sphere radii) and have initial velocities V_y perpendicular to the X-axis. The velocity unit is Jupiter's orbital velocity. The lines mark four classes of stationary orbits — D, N, S, R. Dots label the stable orbit boundary beyond which the particle escapes Jupiter during the course of 100 terrestrial years. The dashed line $V_y = -2X$ corresponds to the velocity profile for epicyclic orbits in the absence of the planet.

under the perturbing action of the Sun [131]. Satellite formation is possible only in a 'cool' disk where the velocity dispersion of the particles is small and encounters lead to coalescence and not to disruption [141]. Obviously, the protosatellite 'cool' disk can consist only of prograde D-orbits or retrograde R-orbits [131]. Therefore, the prograde protosatellite disk is situated within $0.4R_{\mathrm{h}}$. Here the prograde satellites which have not undergone significant evolutionary changes must also reside.

At the pericentre of Jupiter's orbit, the outer radius of the prograde disk is about 18.5 million km [131]. The large semiaxes of the prograde outer Jovian satellites are 11–12 million km, whereas those of the retrograde satellites are 21–24 million km, i.e. the latter are situated just beyond the prograde disk limiting boundary. This confirms the limitation of the prograde disk radius and is evidence for the existence of an outer protosatellite disk. The real boundary to the retrograde disk from the point of view of stability is the Hill's sphere. Only marginal stability exists for the particles in R-orbits beyond the Hill's sphere.

Each asteroid, even the smallest, is surrounded by a zone of stable satellite motion. As a rule, the asteroid satellites lie at a distance of a few asteroid radii (see Table 2). Even for asteroids from the vicinity of the Earth, the Hill's sphere boundary is not less than 200 asteroid radii, and the size of the circular motion zone is about 100 radii [see Eqn (3)]. This means that neither solar, nor weaker Jovian perturbations can destabilise the asteroid's satellite.

5.3 Accretion cosmogony of the protosatellite disk

Protosatellite disks may result from the accretion of gaseous masses and planetesimals from heliocentric orbits. Free motion of a planetesimal to a planet (here the term 'planet' relates to asteroids as well) leads to 4 possibilities:

Table 2. Satellite systems of planets and asteroids.

Planet name	Hill's radius (% R)	Planet mass (in Earth units)	Relative satellite mass (in 10^{-4} of M_{pl})	Relative distance to mass peak (in R_{pl})	Number of satellites
Jupiter	6.7	318	2	6.0 (Io)	16
Saturn	4.6	95	2	20.3 (Titan)	18
Neptune	2.6	17	2	15.9 (Triton)	8
Uranus	2.4	15	1	18.5 (Titania)	15
Earth	1.0	1	120	60.3 (Moon)	1
Mars	0.48	0.1	0.0002	2.8 (Phobos)	2
Pluto	0.13	0.002	1500	17.0 (Charon)	1
Ceres	0.07	3×10^{-4}	?	?	?
Sylvia	0.02	6×10^{-6}	2000	2	1?
Herculina	0.02	4×10^{-6}	80	9	1?
Diotima	0.02	3×10^{-6}	600	4	1?
Metis	0.009	8×10^{-7}	800	14	1?
Ida	0.002	7×10^{-8}	0.7	6	1
Toutatis	0.0002	5×10^{-12}	7500	2?	1

1. Free fly-by after a single approach to the planet (sometimes after 2–3 turns around it).
2. Fall onto the planet.
3. Encounter with a particle from the satellite disk.
4. Encounter with a neighbouring planetesimal.

After the encounter, new choices appear:
1. Transit to a heliocentric orbit.
2. Fall onto the planet.
3. Transit to a relatively stable satellite orbit, prograde or retrograde.

After transit to a satellite orbit, the fate of the body is determined in secondary collisions with other particles. In the Solar System, we deal with three different cases of such an accretion problem for:

— giant planets: Jupiter, Saturn, Neptune and Uranus. A feature of these systems is that the Hill's sphere size constitutes a significant fraction of the orbital radius (see Table 2). Therefore, one can consider a two-dimensional problem of planetesimal accretion from heliocentric orbits onto a protosatellite disk. In case of Jupiter, Saturn and Neptune the planetesimals move approximately in the plane of the protosatellite disk. The situation is more complex for Uranus which lies 'on its side' and the orientation of its satellite system is perpendicular to the ecliptic;

— Earth group planets: Earth, Mars and Pluto. In this case the Hill's sphere is significantly smaller in size than the distance to the Sun, and therefore the accretion growth of the protosatellite disk must be considered as a three-dimensional problem (the particles fall onto the disk from all directions). Both for giant planets and the Earth group planets, chaotic velocities of the planetesimals are commensurate with the escape velocity from the surface of the largest body;

— large and small asteroids: from Ceres to Toutatis.

This is also a variant of three-dimensional accretion but with smaller relative sizes of the Hill's spheres. The most important difference from the Earth group planets is that under Jupiter's action the present fly-by velocities of the planetesimals near an asteroid are many times higher than the orbital velocity of the satellite particles or the escape velocity from the asteroid's surface (as was mentioned above, the velocity of mutual collisions for bodies in the asteroid belt is 5 km s^{-1}, whereas the escape velocity is 0.5 km s^{-1} for Ceres and about 1 m s^{-1} for Toutatis). This complicates the accretion and formation of satellites in the present time.

5.4 Formation of satellite systems around giant planets

The diversity of satellite systems around giant planets is astonishing. The Voyager spacecraft revealed a striking world of outer planet satellites: powerful sulphur volcanoes on the orange Io; many kilometres of geysers of liquid nitrogen on the rose Triton; Titan embedded in deep clouds which possibly hide a carbon–hydrogen ocean. The total number of satellites around the giant planets reached 57.

Moving away from Jupiter, small inner satellites are exchanged for enormous Galilean moons. Beyond the fourth giant, Callisto, an extensive empty space extends from 1.9 to 11 million km. At distances 11–12 million km from Jupiter four more minuscule satellites, the Himalia group, orbit around the planet, and further on empty space stretches again up to 21 million km. And at the very edge of the Jovian system 4 more satellites of the Pasiphae group orbit around Jupiter with semimajor axes in the range 21.2–23.7 km. The most striking aspect is that the satellites of the Pasiphae group revolve in the retrograde direction.

Beyond the famous ring of Saturn, the space is filled by a number of small satellites that grow in size with increasing orbital radius. Among the Saturnian satellites, the largest is Titan, at a distance of 1.2 million km. Then come smaller Hyperion and Iapetus (the latter at a distance of 3.56 million km). At the edge of the Saturnian system at a distance of 13 million km, we meet the unexpected Phoebe, which has retrograde revolution. Note that the mass of Phoebe is more than an order of magnitude higher than the total mass of the retrograde Jovian satellites.

The similarity between the Jovian and Saturnian systems is beyond doubt: diverse groups of prograde satellites are located close to the planet whereas the retrograde satellites are located in a remote periphery of the system. However, the Neptunian system immediately violates the sketched rule: a number of small satellites beyond the outer boundary of the exotic system of Neptunian arches and rings is terminated by Proteus at a distance of 118 thousand km, followed by the enormous

Table 3. Characteristics of protosatellite disk models.

Model number	Prograde and retrograde disk. Number of					Starting angle
	satellite orbits	planetesimal trajectories	orbit and track intersection points	debris cloud trajectories	components	
			JUPITER			
1	11 + 23	23 + 29	363 + 1037	1815 + 5185 = 7000	5	15†
2	27 + 35	88 + 92	4003 + 5569	20015 + 27845 = 47860	5	45†
3	27 + 44	789 + 306	48815 + 25468	439335 + 229219 = 668547	9	180‡
			SATURN			
1	19 + 25	27 + 30	840 + 1200	4200 + 6000 = 10200	5	75†
2	19 + 25	497 + 139	21874 + 6613	196866 + 59517 = 256383	9	180‡
			NEPTUNE			
1	18 + 20	455 + 509	8548 + 11860	76932 + 106740 = 183672	9	180‡
				The total number: 1173662		

† Published in Ref. [131].
‡ Published in Ref. [140].

retrograde Triton (with a radius of 1353 km) at a distance of only 355 km from the planet. And, as if to place before cosmogonists the final ambiguity, a small prograde satellite, Nereid, is situated furthest (at 5.5 million km) from Neptune.

The compact and highly regular system of 15 satellites of Uranus is principally different from other satellite systems around giant planets in having a vertical orientation of the orbital plane (Uranus and its entire satellite system lies 'on its side'). The direction of orbital rotation for all Uranus satellites coincides with the intrinsic rotation of the planet itself.

Such a dramatic difference between the satellite systems of the four giant planets, at the first glance, makes it meaningless to search for a general theory of the formation of these systems. The construction of a model that describes the formation of all the main groups of satellites of Jupiter, Saturn and Neptune is so much the more remarkable [131, 140, 142].

Let us consider the following problem: there exists already a 'seeding' protosatellite disk around a planet (asteroid) with prograde rotation. The probability of collision of a planetesimal with a particle from the disk is determined by the optical thickness of the disk. The encounters change both the surface density and the optical thickness, which changes the probability of capture of planetesimals. In numerical calculations, this process is of an iterative character: after bombardment of the disk and a change of density not more than 10–20% of the initial one, the probability of interaction of the planetesimals with the disk particles is calculated again and the cycle repeats. Such a problem has been solved for Jupiter, Saturn and Neptune [131, 140, 142] in the following cases:

1. Planet and a constant mass in a circular orbit.

2. The initial prograde disk is modelled by a set of D-orbits, and the retrograde motion zones that appear by a set of R-orbits.

3. After impact of a planetesimal with a satellite particle, motion of the centre of mass of debris (for 5 or 9 ratios of the planetesimal and particle masses from 0.1 to 1000) is considered.

Table 3 shows characteristics of the calculated models. The results of calculations of the centre of mass motion of the debris are:

1. Light and moderate planetesimals with a mass of 0.1 and 1 disk particle mass are captured in the prograde satellite orbits.

2. Heavy planetesimals (10 times as massive as the disk particles), by carrying away a part of the debris (38% of all trajectories of the debris end up as heliocentric orbits), are captured in the retrograde orbits to a significant degree: 25% of trajectories for Saturn in model 1, 15.4% of trajectories for Jupiter in model 2. Much less often such planetesimals are captured in the prograde orbits: 7.1% of trajectories for Saturn-1, 11.3% for Jupiter-2.

3. Super-heavy planetesimals (100 times as massive as the disk particle): retrograde captures in 3.6% of cases for Saturn-1, 5% for Jupiter-2; prograde captures in 0.1% of cases for Saturn-1 and 0.5% for Jupiter-2. A fraction of even heavier particles with a mass of 1000 masses of the disk particles transits in retrograde orbits.

A small portion of captures for heavy (10–100 disk particle masses) particles can be decisive for the protosatellite disk evolution, because of their significant mass. It is usually assumed that bodies with mass ratio of the order of unity are effectively captured in accretion models [126].

For each of the six models an 'array of fates' has been constructed for all clouds of debris, according to which a special code calculates the change of the surface density of protosatellite disks for different initial parameters. These results for Jupiter (model 3), Saturn (model 2) and Neptune are shown in Figs 17–19. The position of real groups of prograde and retrograde satellites coincides strikingly with the density profile calculated in the framework of a rather simple model. Coming from Jupiter to Saturn and Neptune, only one significant parameter of the model changes — the time of evolution, which can be easily connected with the known fact of slow growth of remote planets [126].

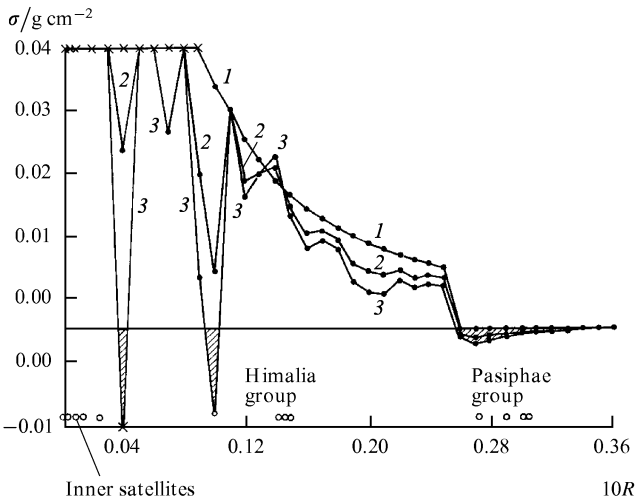

Figure 17. Change in the surface density of the prograde protosatellite disk of Jupiter (model 3) as a function of radius R and time T ($T = 0$ for curve *1*, $T = 0.5$ million years for curve *2*, $T = 0.7$ million years for curve *3*; time step is 0.1 million years). The time scale is of illustrative character and depends on the accepted parameters of the medium of the disk and planetesimals. The negative density corresponds to the zone of retrograde motion (hatched). The filled circles mark Jovian satellites. The rapidly increasing inner density peak lies beyond the figure frame and corresponds to Galilean satellites. The Himalia group of prograde satellites is located close to the unique (in the outer disk zone) region of density increase. The Pasiphae group satellites revolve in retrograde direction. Two more simple models (Jupiter-1,2) give similar results.

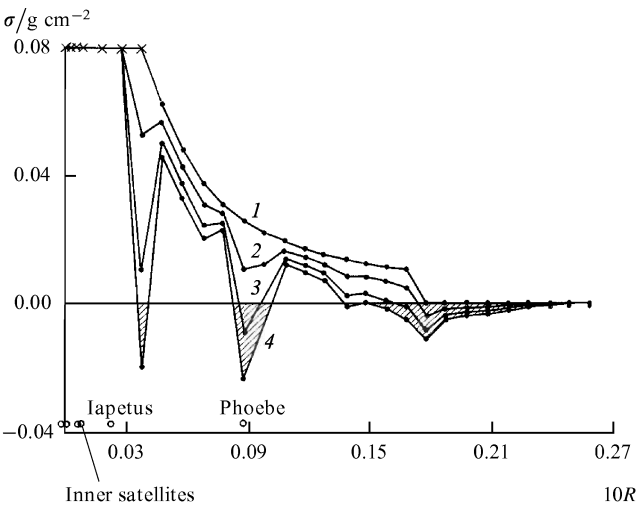

Figure 18. Change in the surface density of the prograde protosatellite disk of Saturn (model 2) as a function of radius R and time T ($T = 0$ for curve *1*, $T = 1.35$ million years for curve *2*, $T = 2.25$ million years for curve *3*, $T = 2.7$ million years for curve *4*; time step is 0.45 million years). The filled circles mark Saturnian satellites. The inner density peak corresponds to inner satellites and the massive Titan. The retrograde satellite Phoebe corresponds exactly to the zone of retrograde particle storage.

Apparently, the modern view is that the satellite systems of giant planets were formed at the very last phase of the planet's growth: between the termination of intensive gas accretion and the ultimate exhaustion of the reservoir of hard planetesimals. In fact, the accretion model gradually excluded stochastic theories of satellite capture from planet

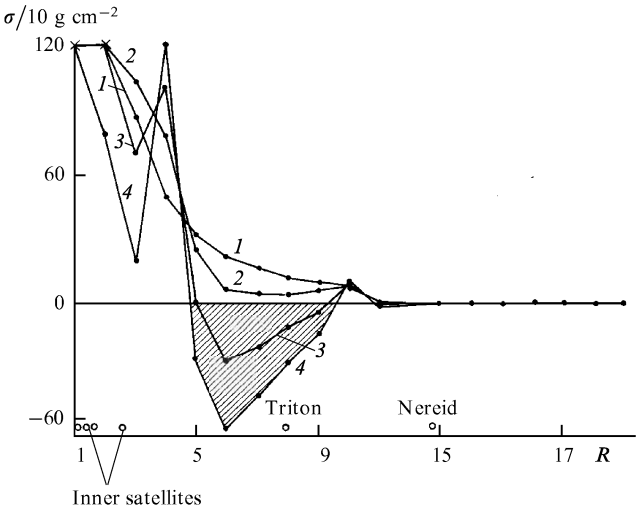

Figure 19. Change in the surface density of the prograde protosatellite disk of Neptune ($T = 0$ for curve *1*, $T = 2$ million years for curve *2*, $T = 3$ million years for curve *3*, $T = 3.5$ million years for curve *4*; time step is 0.5 million years). The enormous retrograde satellite Triton is located inside the zone of retrograde particle storage.

cosmogony. The next problem is to expand the accretion theory to massive satellites of the Earth group planets and to asteroid satellites.

5.5 Growth of satellites of the 'Earth group' of planets

A complex, sometimes even dramatic, interlacing of cosmogonic theories arose around the Moon. As yet, there are no numerical models describing satellite formation around the Earth group planets, therefore let us estimate, based on qualitative considerations, possible modifications to the scenario of satellite formation when moving from giant planets to planets of lower mass.

The time scale of accretion formation of a satellite from the disk by mutual coalescence of the particles is proportional to the revolution time of the satellite [121] and hence depends on the ratio of the satellite's orbital radius to that of the planet. As is seen from Tables 2 and 4, asteroid satellites, as a rule, are located closer to the central body than giant planet satellites and, hence, must grow faster. In terms of satellite distance from the planet, Earth and Pluto fall within an anomalous category of planets which are likely to have had strong tidal evolution, which moved the satellite from the planet to a significant distance. The tidal action might significantly change the orbit of many massive asteroid satellites (see Section 5.7).

The conclusion about rapid satellite growth around small planets and asteroids is extremely important: a satellite that has formed before the protosatellite disk growth has stopped radically changes the entire accretion process. Before a large satellite is formed, the major part of the planetesimal matter captured by the disk falls onto the planet. The rapidly growing satellite will consume a significant fraction of the disk matter. The more massive the satellite, the more actively it consumes the adjacent mass due to the increase in the capture cross section. In addition, as preliminary numerical calculations for the Pluto–Charon system show (Gor'kavyi 1993, unpublished), a massive satellite destabilises outer satellite orbits up to significant distances and captures matter

Table 4. Tidal evolution efficiency for different satellite systems.

Planet's name	Relative mass of satellite (in M_{pl})	Relative distance to satellite (in R_{pl})	Time of orbital change (in 10^9 years)
2 Pallas	9×10^{-4}	4	0.4
		5	3
9 Metis	0.06	14	340
18 Melpomene	0.04	11	110
49 Pales	0.05	6	3
87 Sylvia	0.2	2	6×10^{-5}
146 Lucinia	8×10^{-5}	23	7×10^{6}
171 Ophelia	0.04	7	10
		4	0.2
243 Ida	1×10^{-4}	6	2×10^{4}
423 Diotima	0.05	4	3×10^{-2}
433 Eros	1	7	14
532 Herculina	0.008	5	40
1220 Crocus	0.3	5	9

from them, thus expanding even more its 'consuming' zone (like an impatient child who shakes the upper branches for apples). By consuming the disk matter, the satellite may take up angular momentum as well — if it intercepts particles near their orbital pericentre, where the particle velocity exceeds the satellite's orbital velocity. This prevents the satellite from falling onto the planet. Apart from that, massive satellites of the Earth group planets may move away from the planet under the tidal action. Thus, in the case of the Earth – Moon system we are dealing with a new type of satellite accretion formation, namely, with accretion onto two bodies when the captured planetesimal matter is redistributed between the planet and the large satellite [121].

Owing to the two-body accretion mechanism, the relative masses of satellites of minor planets may significantly exceed the masses of satellites of the giant planets. This conclusion about the increase of the relative mass of the satellite with decreasing mass of the planet implies that the massive Moon and Charon are the rule, whereas Mars and some asteroids are, in contrast, anomalous systems with low-mass satellite systems due to Jupiter's influence, heating up the asteroid belt and 'bombarding' Mars with a large number of planetesimals. Note that the Earth group planets (and asteroids as well) have most frequently a single satellite, which confirms the similarity of their satellite formation mechanisms.

5.6 Formation of asteroid satellites

There are two principal questions in asteroid satellite cosmogony: when were these satellites formed and how have they managed to survive?

Apparently, asteroid satellites were formed at a protostage prior to the heating up of the asteroid belt by Jupiter. In the very flat initial belt of minor planets both protosatellite disks and satellites themselves may appear even around 1 km asteroids. At that stage the mutual velocities of bodies in the asteroid belt were so small that asteroid satellite formation proceeded by the two-body accretion scheme typical of the satellites of the Earth group planets. Therefore, formation of a single satellite should be characteristic of asteroids, but the presence of several satellites and even a ring of small bodies is not excluded. An enchanting vision of myriads of miniplanets with protosatellite disks, rings and satellites contrasts sharply with the traditional view of asteroids as a heap of building garbage.

A difficult question to answer is: how have asteroid satellites survived until now? The contemporary mean velocity of relative motion in the asteroid belt is about 5 km s^{-1}, while the escape velocity from the surface of Ida is 30 m s^{-1} and from Toutatis' surface about a metre per second. Thus, every present encounter of Ida or Toutatis (and their satellites) with another asteroid could result in the total disruption of the body. As numerical calculations show (see e.g. Ref. [143]), during mutual impact of an asteroid with an impacting body a shock wave passes through the asteroid and smashes rocks to pieces, and then the asteroid's fragments, weakly bound by gravitation, disperse.

In the course of the asteroid belt heating up because of Jupiter's influence, the process of growth of the asteroids themselves and their satellites was stopped or slowed down sharply. Some asteroids lost their satellites under the action of mutual gravitational perturbations and catastrophic collisions; in the remainder, a significant erosion of both the main body and the satellite took place. One may expect many asteroid satellites to have a significant eccentricity and inclination to the central body equator because of strong impacts. Nevertheless, a substantial number of asteroids could avoid catastrophic collisions and keep their satellites safe. With account of the destructive factors, a realistic estimate for the current number of asteroids with satellites is about 10%. Probably, this percentage was significantly higher at earlier times: the fraction of bodies with satellites decreased not only as a result of satellite destruction, but also because of the appearance of the secondary 'satelliteless' population of asteroids that arose during collisional destruction of the primary, more ancient bodies. Thus, the presence of that satellite can indicate an earlier formation time of the asteroid. It is not excluded that with heating-up of the asteroid belt the relative mass of newly formed satellites gradually decreased until the process of satellite formation had stopped.

Establishing a connection between the asteroid's spin period and the presence of a satellite would enable one to evaluate the initial number of asteroids with satellites. The role of the protosatellite disk in the acquiring of angular momentum by the central body can be very important [144], but this question is poorly studied as yet and is one of the most complicated problems in cosmogony. It is possible that the direction of the spin axis of a planet and its angular momentum are determined by the presence and orientation of the protosatellite disk which usually takes (for the main planets) one of two orientations: close to the ecliptic plane, as for the majority of planets, or perpendicular to the ecliptic, as for Uranus and Pluto. The orientation of asteroid spins may be more chaotic due to the small masses, the Hill's sphere sizes and subsequent collisions. It is not impossible, however, that the orientation of asteroid protosatellite disks is set up in the early stages of disk formation and changes weakly during the accretion. The problem of the relationship between the satellite orbit and orientation of the asteroid spin axes is extremely interesting. If a cosmogonical connection exists between the central body rotation and satellites, one can expect

asteroid satellites to revolve mainly in the prograde direction (with respect to the asteroid's spin).

5.7 Evolution of asteroid satellites

The main evolutionary factors of satellite systems after their final formation are:
— tidal interaction with the planet;
— mass and angular momentum change due to bombardment by external bodies (meteorites);
— braking by solar radiation (Poynting–Robertson effect);
— aerodynamic braking by the planet's upper atmosphere;
— resonant gravitational interinfluence of the satellites.

If we consider evolution of a particular asteroid satellite which has no atmosphere, only the first three evolutionary mechanisms listed above should be studied. The lifetime of a satellite particle determined by the Poynting–Robertson effect is proportional to the particle radius and is about a billion years for a 3 cm main belt particle. Now consider the efficiency of the satellite mass and angular momentum change caused by meteorite bombardment. Note that one of the most important differences between planet and asteroid satellites is the orbital velocity. The former move with velocities of tens of kilometres per second, whereas orbital velocities of the asteroid satellites fall within a range from one to a hundred metres per second. This means that a satellite escapes from an asteroid much more easily than from a planet. Debris of impact can easily escape the sphere of the asteroid's attraction, leading to a constant mass decrease for both satellites and asteroids. However, even without doing numerical calculations, one can conclude that this mechanism, the efficiency of which is proportional to the surface area of the body, should not destroy all the satellites formed, as the asteroids themselves have not yet disappeared as a result of meteorite erosion.

An important factor is the satellite's angular momentum change during its bombardment by meteorites. Note that under an isotropic bombardment the satellite slows down and thus its orbit must constantly decay. Encounters with large bodies may either accelerate the satellite (or its debris) until it escapes orbit or slow it down to touch the asteroid. The rate of orbital radius change due to tidal interaction with the planet is [145, 146]:

$$r^{-1}\frac{\mathrm{d}r}{\mathrm{d}t} = 2(3\pi G\rho)^{1/2} K_2 \sin(2\varepsilon)\,\frac{m_\mathrm{s}}{r^{13/2}}\,, \tag{4}$$

where m_s is the satellite's mass measured in terms of the planet's mass, r is the satellite's orbital radius measured in terms of the planet's radius, ε is the angle between the tidal hump and the direction to the satellite. For small angles $\sin(2\varepsilon) = Q^{-1}$ where Q is the quality factor of a planet of density ρ. Love's number for a homogeneous sphere [145, 146] is

$$K_2 = \frac{3}{2}\left(1 + \frac{57\mu}{8\pi G\rho R_\mathrm{pl}^2}\right)^{-1}\,, \tag{5}$$

where μ is the rigidity of a planet of radius R_pl. The first term in the denominator can be neglected for asteroids. Table 4 presents parameters of the known asteroid satellite systems (systems taken from Table 1 for which both the satellite's size and its orbital radius are known) together with characteristic times of orbital change calculated according to Eqns (4) and (5). For all bodies the following parameters were taken: $\mu = 5\times10^{11}$ dyn cm^{-2}, $\rho = 3.5$ g cm^{-3}, $Q = 1000$ [145] (the value of Q is highly uncertain and we note that the evolutionary time is directly proportional to Q). If the period of the satellite's revolution is greater than the asteroid's spin period (as is the case for the Earth–Moon system), the tidal hump on the asteroid caused by the satellite anticipates the satellite due to dissipative effects thus accelerating its revolution (in a frame rigidly rotating with the central body) and moving it to a higher altitude orbit. If the satellite revolves faster than the planet itself (as in the case of Mars–Phobos), it is slowed by the lagging tidal hump and falls onto the planet. The evolution of the satellites moving away gradually slows down, and the orbital increase for such systems must naturally be very slow at the present time — with a characteristic time comparable at least with the cosmogonical time scale. In contrast, the satellites which are braked speed up their evolution, and if they have not so far fallen onto the planet, they may well do so during a short time period (like Phobos). There should be no tidal orbital evolution in the case of resonance — if the satellite's orbital period is equal to the planet's rotational period (as in the case of Pluto–Charon). One may conclude from Table 4 that the tides play an important role in the evolution of asteroid satellites. Note that out of 12 satellite systems in Table 4 only Sylvia's and Diotima's exhibit a rapid tidal evolution. According to Section 4.3, the Diotima system is synchronous, therefore the evolutionary time obtained for a given value of the lag angle (equal for all asteroids) between the tidal hump and the direction to the satellite does not relate to the Diotima system. The time of revolution of Sylvia's satellite differs by 2%, according to Section 4.2, from the spin period of the asteroid itself. This, on the one hand, may imply synchronism; on the other hand, even if difference is real, the planet's rotation velocity relative to the satellite is so small that the deviation angle of the tidal hump must be very small (due to dependence of the dissipation function on the load frequency). This leads to a sharp slowing down of the tidal evolution of Sylvia's satellite. The evolutionary time for other satellites (which are apparently slow and moving away) is long enough, as is demonstrated by their present stability. A large number of contact asteroid systems can be explained by an effective tidal braking of a satellite which has formed close by and is rapidly revolving.

6. Conclusions

Preliminary results show that up to 10% of asteroids may have satellites. Because of the difficulty of carrying out astrophysical observations of the majority of asteroids, it is not surprising that the number of discovered double asteroids is small as yet. The data presented in the review should help for preparing specially aimed searches for double asteroids, taking into account the indicators of binarity. Use of the methods of frequency analysis opens new opportunities for studying the dynamic structure of asteroids on the basis of widely spread photometric observations. The existence of double planets (Earth, Pluto) and binary asteroids should be considered as a general rule. The presence of satellites around minor planets should also be determined by mechanisms common for all planets. Therefore, precise determination of the structure and the physical nature of asteroids would shed new light on many puzzles of the evolution of the large planets. The study of asteroids is significant not only for

our planetary system. The discovery of accretion disks around many stars has stimulated interest in the cosmogonical problems of other planetary systems, which cannot be solved without a correct theory of the formation of the Solar System formation. Note that young massive planets would disperse some of the asteroids thus causing a bombardment of the inner planets and the central star itself. After studying the spectral variability of β Pictoris (a unique photograph of the protoplanetary disk around this star was taken in 1984 [147]), it became clear that a similar asteroid – cometary bombardment takes place there with an intensity of 200 comets per year [148]. Studies of the details of this amazing process show that it is caused by two planets: an inner Jupiter-like one and an outer younger one similar to Saturn [149, 150]. Asteroids thus are a key to understanding the formation processes of many planetary systems. Although Jupiter has significantly influenced the asteroid belt evolution, the existence of asteroid satellites is a direct consequence of and evidence for peculiarities at early stages of planetesimal evolution. If the hypothesis about the formation of satellites around small planets at the initial stage of planetesimal formation is true, modelling of the conditions under which satellites appeared would provide important information about the characteristics of the planetesimal disk before it was influenced by Jupiter. Future comparative analysis of satellite systems around small and large asteroids located in different zones of the asteroid belt would give an idea about the rate and character of the heating up of the main belt. More data on asteroids with complex structure would lead to an important extension of the observational basis for cosmogonical theories and should modify theories of satellite system formation and possibly also theories of planetary formation.

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