25 YEARS OF ASTEROID INVESTIGATIONS BY KHARKIV ASTEROID GROUP

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In the middle of the 1970s physical investigations of asteroids became quite active in the USA and partly in Europe (Italy, Austria, Sweden). It was evident that asteroids are the bodies of great interest first of all from the point of view of cosmogonic problems of the Solar System. That was the principal reason for the beginning of asteroid studies at our Institute (Astronomical Observatory, at that time). The most important results of asteroid study obtained by our group during the last 25 years are presented.

PHOTOMETRY

The first observations of asteroids in order to study their physical properties were started together with our colleagues from the Institute of Astrophysics of the Tadjik Academy of Sciences at the Gissar Observatory in July–August 1977 with the 70-cm reflector and photoelectric photometer. Those photometric observations were oriented to the derivation of lightcurves and magnitude–phase dependencies for asteroids of various types. In particular, such data were obtained for the biggest M-type asteroid 16 Psyche for two oppositions. In 1978, its lightcurve amplitude was near zero opposite the maximum amplitude (0.35 mag) in 1979. This means that in 1978 we observed Psyche at pole-on view, that is, along the rotation axis and the coordinates of the asteroid were close to the coordinates of its pole. Besides, the magnitude of the asteroid in 1978 at pole-on view is about 0.45 mag larger than at equator-on view in 1979, that is, in 1978 we observed a larger asteroid cross-section than in 1979. This means that Psyche rotates around the shortest axis keeping the maximal momentum of inertia (Lupishko, Belskaya [13]). Today, we know that it is principal axis rotation, regular for asteroids, but 20–25 years ago it was not so obvious, and we obtained one of the first confirmations of that from our photometry.

The opposition effect (OE) of brightness of asteroid surfaces has been a subject of our interest since our first photometric observations. Now the study of magnitude–phase dependencies and opposition effect of asteroids is one of the basic programs of our group; V. Shevchenko carries out the systematic observations of asteroid brightness near oppositions up to limitedly small phase angles ($\sim 0.1°$). He obtained the magnitude–phase dependencies of some low-albedo asteroids, *e.g.,* 59 Elpis, which show a very small value of OE. The analysis of all available data showed the complex and ambiguous dependence of amplitude of OE on asteroid albedo (Belskaya, Shevchenko [5]). The different taxonomic classes of asteroids have different OE amplitude, and this result is very important for understanding mechanisms forming the OE and for study of the structural and compositional differences in asteroid surfaces. This result should be taken into account for ephemeris and other computations of asteroid absolute magnitudes as well.

Another direction of our photometric observations is the determination of shapes and rotation parameters of asteroids (rotation rate, sense of rotation and pole coordinates, that is, orientation of the rotation axis in space). Our contribution to these data storage is rather essential: about one hundred asteroid periods of rotation determined and about 50 asteroids with all determined parameters listed above ($\sim$25% of all available data). Analysis of all these data (about 200 asteroids) shows that the anisotropy in the distribution of ecliptic latitudes of asteroid poles takes place only for objects with prograde rotation (for asteroids with retrograde rotation the distribution is nearly isotropic). At the same time the degree of anisotropy increases with asteroid diameters. Besides, it was shown for the first time that the ratio of asteroids with prograde and retrograde rotations increases with their diameters from 1:1 among small asteroids ($D < 50$ km) to 1.5:1 among intermediate asteroids ($50 < D < 125$ km), and to 2:1 among large ones ($D > 125$ km). Both these conclusions have a cosmogonic character and are evidence of the intensive collisional evolution in asteroid belt (Tungalag *et al.* [28]).

The clear minimum at $D = 125$ km in the dependence of a fraction of asteroids with retrograde rotation on their diameters (revealed by Lupishko and Velichko [21]) was confirmed using a sample of data which is 2.5 times larger that the sample analysed before. Similar minima at this diameter take place also in the dependencies of rotation rates and lightcurve amplitudes on asteroid diameters. And what is more new and more complete data show that the depth of the minimum can depend on asteroid type, that is, on asteroid density. Thus, asteroid diameter $D = 125$ km is some cosmogonic peculiarity, and its quantitative explanation can give new and important information on dynamical evolution in asteroid belt (Tungalag *et al.* [28]).

Concerning the pole coordinate determinations, it should be emphasized that while doing this work we payed attention to the procedures of the determination and tried to improve them. During the last two years we have undertaken the special program for determination of asteroid shapes and parameters of rotations including the pole coordinates, using the photometric model of asteroid developed by our group (Shevchenko [26]), combined method (amplitude-magnitude plus photometric astrometry), the Akimov law of light scattering (Akimov [1]) and other new elements (Tungalag *et al.* [27, 28]). That is why our determinations for the most part are more accurate then those of other authors.

Now, one of our main programs is photometry of near-Earth asteroids (NEAs); Yu. Krugly is the principal performer of it. More than one hundred of NEAs have been observed by now and about 450 of their lightcurves have been obtained. The scientific problems remain mostly the same as for main-belt asteroids though they are supplemented sometimes by astrometric observations of the newly discovered NEAs in the framework of European Program of Hazardous NEO Discovery. Yu. Krugly's Ph. D. Thesis (Krugly [10]) contains the principal results of this program. Among them the lightcurve for the apollo asteroid 4179 Toutatis obtained by our group within the International campaign in 1992–1993. The American colleagues noted that Kharkiv group obtained the most accurate value of Toutatis' period (176 hr) which turned out to be the period of precession. Photometric data together with radar data evidence that Toutatis has a very complex non-principal axis rotation. Yu. Krugly and V. Shevchenko obtained the magnitude–phase dependence for 433 Eros down to $\alpha = 0.3°$ which was used by USA colleagues for interpretation of the results of NEAR-mission to NEA 433 Eros.

At present, Yu. Krugly collaborates effectively with P. Pravec (Czech Republic) in discovery and study of binary systems among the NEA population. By photometric method, they discovered four binary systems among the NEAs and determined their parameters (Pravec *et al.* [22], Krugly [10]). The table gives the results of that investigation (D is diameter, R and P_{orb} are orbital radius and period of the secondary body, P notes period of axis rotation, and A is lightcurve amplitude; indices 1 and 2 correspond to the primary or the secondary body).

Binary asteroid	Type	D_1, km	P_1, hr	A_1, mag	D_1/D_2	P_{orb}, hr	R/D_1
5407 1992 AX	C	4.0	2.549	0.13	≥0.30	13.52	(1.7)
31345 1998 PG	(S)	0.9	2.516	0.13	≥0.30	14.01	(1.7)
1996 FG3	C	1.4	2.594	0.08	0.31	16.14	1.7
1999 HF1	S	3.5	3.319	0.13	0.24	14.02	2.0

POLARIMETRY

Polarimetric studies of asteroids started at the Gissar Observatory (Tadjikistan) as well, together with N. Kiselev and G. Chernova. One of the first programs was polarimetry of CMEU-asteroids, proposed by I. Belskaya. It turned out that nine of the observed 12 CMEU-asteroids belong to M-type ("metallic"). By then (1987), the total number of M-asteroids increased to 24 objects and available data confirmed with confidence their relatively faster rotation and more elongated shapes as compared with C- and S-types (Belskaya *et al.* [3, 4]).

The study of polarization–phase dependences of the selected main-belt and near-Earth asteroids is one of the polarimetric programs of our group. Our data have confirmed the unique polarimetric property of large main-belt asteroid 704 Interamnia, namely, minimal value of inversion angle (15.7°). The phase curves of polarization of NEAs Ganymed, Ivar, and other asteroids obtained for the first time, gave the albedos of the asteroids with a rather high accuracy. Within our All-Union program "Vesta-1986", N. Kiselev and A. Morozhenko, at the Soviet–Bolivia Observatory, carried out simultaneous photometric and polarimetric observations of the asteroid 4 Vesta which showed the clear inverse correlation of brightness and polarization with asteroid axis rotation (Lupishko *et al.* [15]). This is a very important result indicating that a) Vesta lightcurve is conditioned not by the shape of the body but mostly by albedo variation over the surface; b) Vesta has one pair of lightcurve extrema over the rotation period and its period is 5.34 hr but not twice as large as it was thought at that time; and c) Umov's law, that is, inverse correlation albedo-polarization takes place for the negative polarization as well.

Since 1983 we have been collaborating with N. Shakhovskoj and Yu. Efimov (the Crimean Astrophysical Observatory) in *UBVRI*-polarimetry of asteroids with the 1.25-m reflector in order to study the spectral dependence of asteroid polarization. We obtained that absolute value of negative polarization P_{min} of moderate-albedo and high-albedo asteroids of S-, M-, V-, and E-types increased with wavelength similar to those of ordinary chondrites, achondrites, enstatite chondrites, and terrestrial silicate specimens. At the same time low-albedo asteroids similar to carbonaceous chondrites show inverse dependence, that is, decrease of $P_{min}(\lambda)$ (Lupishko [11]).

Our *UBVRI* polarimetric observations of 4 Vesta in 1990 showed the variations of polarization degree over the surface of Vesta which also anticorrelate with brightness. Besides, quite a new result, namely, the variations of polarization position angle of Vesta with its axis rotation was obtained. The amplitude of variations is maximal in U-band and equal to 8°. Our additional observations of Vesta in 1996 gave even larger amplitudes of the variations. The results of comparison of the amplitude and character of the variation with Vesta's topography are in good agreement with the hypothesis that they arise from the presence of orderly oriented linear features on asteroid surface, such as grooves and/or slopes, which are related to the existence of a giant ($d = 460$ km) crater on Vesta, detected by the Hubble Space Telescope (Lupishko *et al.* [16]).

One of new polarimetric results is so-called polarimetric opposition effect of the high-albedo E-type asteroid 64 Angelina, obtained due to the cooperation between the Kharkiv, Crimean, and Main Astronomical (Kyiv) observatories. Besides the opposition spike in brightness of E-asteroids, revealed by Alan Harris, there is also a narrow polarization opposition spike within 3° from opposition, centered at $\alpha \approx 1.5°$, which is superimposed on the regular negative branch. Such phenomenon also takes place for Galilean satellites of Jupiter and both brightness and polarization spike are caused by the coherent backscattering of sunlight by high-albedo surface particles (Rosenbush *et al.* [25]).

The polarization–phase curves of 4179 Toutatis obtained in *UBVRI* (1992–1993) allowed us to analyse the spectral dependence of asteroid inversion angle and of polarimetric slope for the first time. We analysed the phase dependence of polarization position angle for Toutatis in proper coordinate system of asteroid as well. This angle is equal to 0° when polarization degree is positive and to 90° when it is negative. But for three dates (at $\alpha = 16° - 19°$), this angle is equal to about 45°, which points to the presence of Toutatis' polarization unconnected with the scattering plane. It is the only case among atmosphereless bodies, and one of possible explanations of it may be the effect of surface heterogeneities and the extremely complex asteroid shape (Lupishko *et al.* [20]).

Near-Earth asteroids give us a good possibility to observe the objects at large interval of phase angle and to extend this knowledge to the main-belt asteroids of the same taxonomic classes. In cooperation of three observatories (Kharkiv, Crimea, Golosiiv) a polarization–phase curve of the aten asteroid 33342 (1998 WT24) was obtained for the interval of phase angles from P_{min} to P_{max}. Those data allowed us to derive the parameters of polarization in *UBVRI* bands, to estimate albedo and size of asteroid, to classify it as a high-albedo object of E-type (Kiselev *et al.* [9]) and to obtain a complete polarization–phase curve of E-asteroids. It was quite unexpected that P_{max} of E-type asteroids is about 1.7%. The similar data for the maximum positive polarization were also obtained for S-type asteroid 1685 Toro, and they gave $P_{max} = 8.5\%$ (Kiselev *et al.* [8]).

INTERPRETATION AND DATA ANALYSIS

One of such our works is the study of the surface composition of M-type (metallic) asteroids. By the end of the 1970s, Dollfus *et al.* [6], on the basis of laboratory polarimetric measurements, stated that surfaces of M-asteroids could not be made of silicates but are covered by metal fragments with grain sizes of 20–50 microns. We carried out the special program of photometric and polarimetric observations of the largest M-asteroids and the same laboratory measurements of the silicates, metals and different types of meteorites and showed that the surfaces of at least the largest M-type asteroids (16, 21, 22, 69, and 110) cannot consist of pure metal and contain considerable (up to 50%) silicate component like stony-iron or enstatite chondrite meteorites (Lupishko, Belskaya [14]). This conclusion was confirmed in the 1990s by several investigations carried out in the USA (Rivkin *et al.* [23, 24]). In those investigations, the absorption of hydrated silicates in the surfaces of most observed M-asteroids was found.

The scattering law of asteroid surfaces is a very important characteristic which is used for various purposes. We tried to establish which scattering law corresponds to the asteroid surfaces best of all. It was not simple to do this because asteroids are star-like objects and we cannot measure the distribution of brightness along their equators of intensity. Our idea was to use the integrated-disc characteristic of brightness such as dependence of lightcurve amplitude on asteroid phase angle. The observations gave a linear dependence with a definite slope. Therefore, we have modelled the same dependences for seven known scattering laws and obtained that only the Akimov and Hapke laws correspond well to asteroid scattering. But the Akimov law, which was deduced from the assumption of the extremely rough surface, is much more simpler than the Hapke law (Akimov *et al.* [2]).

Two empirical dependencies, namely, "P_{min} – albedo" and "slope – albedo", are usually used for albedo determination from polarimetric data. These dependencies were calibrated almost 30 years ago using the laboratory polarimetric measurements of meteorite samples. But since then the asteroid albedo sets have been derived from radiometric ground-based, IRAS and occultation observations. We used those data for a new calibration of the polarimetric albedo scale of asteroids and obtained new constants of those dependencies. The new calibration gives better convergence of coefficients of both dependences and is used for asteroid albedo determinations (Lupishko, Mohamed [18]).

IRAS-albedos and diameters of asteroids represent the largest data set which contains these data for about 2000 asteroids and, therefore, they are very often used now. However, these data contain the considerable random and systematic errors. By comparison of the IRAS-albedos with other series of the geometric albedos of asteroids (ground-based radiometric, polarimetric and stellar-occultation albedos) it was shown that: (a) systematic errors in the IRAS-albedo increase in direct proportion to the value of the albedo itself and (b) the polarimetric albedos are intermediate between the IRAS and ground-based radiometric albedos and correspond most closely to the most accurate stellar-occultation albedos. That is why the polarimetric albedos of 127 asteroids, obtained with our new calibration, were used to determine the systematic errors of the IRAS-albedos. The method proposed for improvement of the IRAS-albedo and diameters (Lupishko [12]) gives more accurate values of these parameters in comparison with the original data.

Available data on physical properties of near-Earth and main-belt asteroids clearly indicate that the main asteroid belt is the principal source of NEA origin. But the identification of a few asteroids with extinct or dormant comets does not exclude the cometary origin of some of them. The candidates for cometary origin should be low-albedo objects of D-, P-, and C-types, with lower rotation and more elongated shapes as compared with MBAs of corresponding sizes; they should also have orbits atypical for asteroids (comet-like, with $Q \geq 4.5$ AU) and association with meteor streams. It was shown that no more than 10% of known NEAs satisfied these requirements, that is, no more than 10% can have the cometary origin (Lupishko and Lupishko [17]). This conclusion does not contradict the recent results of dynamic considerations, and it was confirmed by Fernandez [7] and Whiteley [29].

Below are other results derived by our group:

- a photometric model of asteroid which uses arbitrary shape, scattering law, and arbitrary magnitude–phase function of asteroid, is developed. The model is used for study of asteroid rotation, shape and optical properties (V. Shevchenko);
- the Asteroid Polarimetric Database which contains the data of polarimetric observations of asteroids is created. The Database is a part of the Planetary Data System (USA) and is accessible through the Internet (Lupishko, Vasil'ev [19]);
- seven Ph. D. and two Doctor of Sciences Dissertations devoted to asteroid studies were prepared and defended;
- two All-Union seminars, five meetings of Workgroup "Asteroids" and two International Workshops (1997 and 2003) were organized and carried out;
- more than 160 papers and 170 abstracts were published for 25 years (about half of them were published abroad).

Finally, we are represented by three personal and one common asteroids, namely, 3210 Lupishko, 4208 Kiselev, 8786 Belskaya, and 15898 Kharasterteam.

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