STUDIES OF THE PHYSICAL PROPERTIES OF SMALL BODIES OF THE SOLAR SYSTEM IN THE SHAMAKHY ASTROPHYSICAL OBSERVATORY

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1. Introduction

One of the traditional areas of scientific research at the Shamakhy Astrophysical Observatory (ShAO) is the problem of the origin and evolution of minor planets (or asteroids), whose orbits form a belt in the space between the orbits of Mars and Jupiter. In the pioneering works of G.F. Sultanov (later the first director of ShAO, academician of the Azerbaijan National Academy of Sciences), performed in the 50s of the last century, it was shown that asteroids could not form due to the catastrophic collapse of the hypothetical planet Phaeton, as predicted by the popular Olbers hypothesis. After several decades, these ideas were brilliantly confirmed as a result of the growth of information on the physical properties of asteroids (i.e., on the albedo and their surface spectra, diameters, rotation periods and body shape).

At the turn of the 80s, the first spectral observations of asteroids in our country began in the ShAO. In the reflection spectra of asteroids of various optical types, we managed for the first time to detect weak absorption bands of ferrous iron (Fe^{2+}) and trivalent chromium (Cr^{3+}), which played a significant role in understanding the composition of the substance composing their surface. Weak Fe^{2+} bands were also identified in the reflection spectra of V asteroids, making it possible to substantially refine the mineral composition of the surface of these objects. From the reflection spectra of E-asteroids, optically active centers of titanium were detected in the structure of their surface material. This finding led to conclusion about a strongly reducing environment essential to form minerals composing these asteroids.

According to the observations of the Hubble Space Telescope, a remote mineralogical analysis of certain areas on the surface of asteroid 4 Vesta was carried out. Based on this analysis, we came to conclusion that a primary chondrite-like substance, of which other Vesta's rocks and minerals subsequently originated, still persists on the surface of this asteroid.

In the monograph "Optical effects of space weathering in the main belt of asteroids" [1], the influence of exogenous factors (primarily the solar wind) on the findings of remote mineralogical analysis of the surface of small planets was studied. Shock-activated movements of regolith particles counteract the speed of optical maturation of asteroid surfaces. Impact “rejuvenation” of the asteroid surfaces due to the constant removal of fresh matter to the surface determines the adequacy of the spectral analysis of asteroid material composition.

Based on a comparison of the spectral properties of asteroids and interstellar dust, it was concluded that the original material of the protoplanetary nebula, from which the planets of the solar system originated, has been preserved to our time in the form of exotic D asteroids.

The results of our work for more than 30 years were summarized in the review [2] and the monograph “Composition of the substance of asteroids by their reflection spectra” [3]. A brief review of the results of our research in recent years is given below.

2. Polarimetric properties of asteroids

By analogy with the two-parameter HG-photometric function, which according to the MAS solution is used to calculate the stellar magnitudes of asteroids, K. Lumme and K. Muinonen in 1993 proposed a simple empirical formula for calculating the linear polarization of asteroids, comets, and planet satellites [4]. The proposed formula, according to the authors, was able not only to successfully approximate the observed dependences of the linear polarization of small bodies of the solar system on the phase angle, but also correctly predict the degree of polarization for those phase angles ranges that are not available for observations from the Earth.

This approach to the interpretation of polarimetric data also makes sense at the present time, since there is no generally accepted theory of polarization of light diffusely scattered by the rough surface of planets. In addition, polarimetric observations, as a rule, do not cover the phase angle interval necessary for calculating all polarimetric parameters. For example, the asteroids of the main belt are not accessible for ground-based observations at phase angles of more than 30 degrees, i.e. in the region where the degree of polarization reaches its maximum. In addition, comets and asteroids approaching the Earth often do not have measurements of the extreme values of polarization degree, which characterize polarimetric functions at the corresponding phase angles.

As the observational material accumulated, the shortcomings and limitations of formula [4] began to appear both in approximating the observational data and in the task of predicting polarization values [5, 6, 7]. Therefore, we have applied another approximating formula proposed by D. Shestopalov [8] to study the polarimetric properties of asteroids and comets. In the course of these studies, we have repeatedly been convinced that the formula [8] allows us to calculate the phase curves of polarization of asteroids and comets with accuracy comparable to measurement errors. This circumstance contributed to obtaining a number of interesting results in the study of the photometric and polarimetric properties of asteroids and comets.

2.1. Relations between the polarimetric and photometric characteristics of asteroids

Since the theory of polarization of light scattered by the rough surface of planets has not yet been created, the question "what are the characteristic features of the surface of asteroids that determine their polarimetric properties?" remains relevant today. Therefore, it is of interest to study the relationships between the polarimetric and photometric characteristics of asteroids based on high-precision observations collected in planetary databases on the NASA PDS website. To calculate the analytical polarimetric functions from the results of discrete observations of asteroids, we used the 5-parameter formula proposed in [8]:

$$P(\alpha) = \frac{h(1-e^{-m\alpha})(1-e^{-n(\alpha-\alpha_i)})(1-e^{-l(\alpha-\pi)})}{n(1-e^{-m\alpha_i})(1-e^{-l(\alpha_i-\pi)})},$$

where the polarimetric slope h for the inversion angle α_i, as well as m, n and l are free parameters. This formula approximates the observational data with accuracy comparable to the observation errors and allows us to estimate the extrema of the phase curve of the degree of polarization, i.e. P_{max} and P_{min} at the corresponding phase angles α_{max} and α_{min}. In turn, the photometric function of asteroids in the interval of phase angles accessible to observations from the Earth can be approximated using a simple formula proposed by V. G. Shevchenko [9]:

$$\Delta V(\alpha) = -a_{OE}/(1+\alpha) + b\times\alpha ,$$

where ΔV is the change in the apparent magnitude of the asteroid, a_{OE} is the amplitude of the opposition effect (i.e., the excess of the magnitude with respect to the linear part of the photometric function), the phase coefficient b measures the slope of the linear part of the photometric function in the range of phase angles from α_{OE} to $\alpha \approx 30^o$. Using the same formula, we can determine the width of the opposition brightness peak at half its maximum, FWHM, and the phase angle a_{OE} at which a nonlinear brightness begins to increase with decreasing the phase angle.

The total number of asteroids for which it was possible to calculate fairly accurate photometric and polarimetric functions turned out to be small, therefore, a search for correlations between photo and polarimetric parameters was carried out for average data characterizing *E*, *S*, *M*, and *C*-type asteroids. In other words, we searched for correlations between the average values of the polarimetric (h, P_{min}, α_i, α_{min}) and photometric parameters (a_{OE}, b, α_{OE}, FWHM) that characterize these optical types of main belt asteroids.

Such a way led to the discovery of statistically significant correlation dependences between the phase coefficient b and the above polarimetric parameters of the negative branch of asteroid polarimetric curves [10, 16]. In addition, a correlation was found between the photometric parameters a_{OE} and the inversion angle α_i for a number of asteroids from the indicated optical types [11]. No other statistically significant correlations between the remaining pairs of photometric and polarimetric parameters were found.

We also confirmed that there is a close correlation between the phase coefficient b and the geometric albedo of asteroids p_V. According to the widespread opinion, b–p_V interconnection arises due to the shadow effect when light is diffusely reflected by the surface with a very complex microstructure of the uppermost layer, which directly interacts with incident radiation. The latter may mean that the correlations between the phase coefficient and the parameters of the negative branch of the polarimetric curve can also be caused by the shadow effect and, consequently, the surface roughness of the asteroids.

2.2. Negative branch of polarimetric curves of asteroids and surface roughness factor

The statistically significant correlations between the polarimetric parameters h, P_{min}, α_i, α_{min} of the asteroids and the surface roughness factor c explicitly confirm the assumption that the irregularities of the light-scattering surface at the scale of wavelength of the incident light play an important role in the formation of the negative branch of the phase curve polarization of asteroids [12]. In [13], the following formula is proposed for describing the surface photometric roughness:

$$c = (H/L)\times(1-e^{-2\tau}),$$

where H is the average height of the irregularities of the microrelief of the light-scattering surface, L is the average distance between them, and τ is the optical density of the surface material.

The joint use of this formula and the relationship $h – c$ allows us to conclude that the H/L ratio decreases with decreasing albedo of the surface of the asteroids (i.e., in the direction $E>S>M>C$). Such a trend arises because with increasing surface albedo the intensity of mutual illumination of some particles by others also increases. As a result, shadows from surface irregularities are highlighted by neighboring particles, and the contribution of the shadow effect to reflected radiation decreases.

2.3. The degree of surface roughness and the albedo-polarization ratio

In accordance with Umov’s law, the lower the albedo of a surface, the greater the degree of polarization of light diffusely reflected by this surface. In asteroid physics, this principle is used to determine the geometric and spherical albedo of asteroids based on the obtained correlation equations between the surface albedo and its polarimetric parameters h and P_{min}. Despite the fact that these empirical relationships are statistically significant, the scattering of points on the plots "$p_V – h$" or "$p_V – P_{min}$" is significantly larger than the measurement errors. Moreover, the scattering of points with respect to the regression lines does not depend either on the sample size or on the choice of observational data sources. This interesting property of the relations "$p_V – (h, P_{min})$" was the subject of our analysis in [14, 16].

The optical characteristics under consideration depend on the surface roughness factor c (Section 2.2); therefore, the contribution of this parameter to the observed albedo - polarization relationships can be estimated. We have shown that random variations of the roughness factor of asteroid surfaces not only lead to the observed correlations of the "albedo – h" and "albedo–P_{min}", but also explain the data scattering with respect to the regression lines. Since the structural properties of the asteroid surfaces randomly vary from one body to another, an increase in the observational data on albedo and polarization is unlikely to lead to an “improvement” of the "albedo – (h, P_{min})" ratios and to an increase in the accuracy of estimating asteroid albedo from polarimetric data.

2.4. Estimation of P_{max} and α_{max} for main belt asteroids

The range of phase angles, where the polarization degree reaches its maximum (i.e., $\alpha \approx 100^o - 130^o$), remains unavailable for the ground-based observations of the main belt asteroids. The measurements of the parameters of the positive branch of the polarimetric function of the main belt asteroids are possible only from the spacecraft. The problem of predicting the maximum degree of polarization for asteroids, when the polarimetric curve is known only for phase angles less than 30°, was investigated from a mathematical point of view in [5]. Based on our experience of approximating polarimetric functions for near-Earth asteroids (NES) in the range of phase angles of ~ 40–80°, we can expect the following errors in predicting the position of the polarization maximum:

$$\Delta P_{max} / P_{max} \sim 0.1 \text{ and } \Delta\alpha_{max} \sim 5^o .$$

A detailed study of the issue shows [15, 16] that the calculated values of P_{max} and α_{max} for E, S and M asteroids using the approximating formula [8] are close to the values obtained for lunar soil. This kind of identity can arise due to the similarity in composition and microstructure of the surface of the Moon and asteroids from these optical types. In turn, low-albedo C asteroids show a relationship between P_{max} and α_{max}, which is not typical for the lunar soil. Now we cannot determine with certainty whether these differences are caused by our extrapolation or due to the properties of the dark surface of C asteroids.

As the first experience, we positively evaluate the ability of the formula [8] to predict the parameters of the polarimetric function from measurements of the polarization of asteroids at small phase angles. However, this conclusion needs additional verification from observations of asteroids approaching the Earth, which are visible in a wider range of phase angles as compared with the asteroids of the main belt.

2.5. Dependence of polarimetric parameters on wavelength

The analysis of the polarimetric and photometric properties of asteroids in the visible spectrum is limited, as a rule, by the data obtained in the V bandpass. Therefore, it is of interest to ask whether the correlations between the photo- and polarimetric characteristics of asteroids differ in different spectral ranges. For this purpose, we used the databases available on the NASA PDS website and containing the corresponding high-precision measurements of asteroids in the Johnson system UBVRI bandwidths. An analysis of the obtained dependences between the optical characteristics of asteroids leads to the following conclusions [17].

The close relationship between the surface roughness factor $c(\lambda)$ and the phase coefficient $b(\lambda)$ helps to understand the physical meaning of the latter. Variations in the slope of the linear part of the asteroid photometric function in the visible and near infrared spectral regions are caused by variations in the surface roughness factor of the asteroid surfaces.

The regression equations between $c(\lambda)$ and spectral geometric albedo $p(\lambda)$, as well as between $c(\lambda)$ and $P_{min}(\lambda)$, do not differ within the statistical error from the same equations obtained earlier in the V band. This means that the interpretation of these dependences, obtained for the V band, remains valid for multispectral data.

An analysis of the diagrams $p(\lambda) - P_{min}(\lambda)$ and $p(\lambda) - h(\lambda)$, constructed from multispectral data, allows us to conclude that, in general, Umov's law is fulfilled when moving from low albedo asteroids to high albedo ones. However, this law is being violated within individual groups of asteroids united by spectral albedo (i.e., for asteroids with high, intermediate and low albedo values). In other words, the inverse proportionality between the spectral albedo $p(\lambda)$ and the parameters $P_{min}(\lambda)$ and $h(\lambda)$ may be violated for some asteroids. We came to the same conclusion by studying the differences in the polarimetric functions of asteroids obtained in different spectral regions [18].

In [19, 20], we tried to explain the spectral dependence of the parameter $|P_{min}(\lambda)|$ which is observed for a number of asteroids. In the first of these works, we admitted the possibility that the average slope of the microrelief of asteroid surfaces varies with the wavelength. Moreover, this slope correlates with the gradient of the spectral curve and spectral albedo: with increasing the spectral gradient and spectral albedo of the surface, the average slope of the microrelief irregularities also increases. We later discovered that such an approach could lead to a conflict with another optical effect known in planetology as the spectral “reddening” of surface with increasing phase angle.

In [20], we again investigated the spectral behavior of $|P_{min}(\lambda)|$ for asteroids with high-precision measurements of polarization degree in the different bandpass. It was shown that the ratio $|P_{min}(\lambda)|/|P_{min}(\lambda_0)| = P_{min}(\lambda/\lambda_0)$, which can be called a polarimetric color index, depends on the spectral color index $R(\lambda)/R(\lambda_0) = R(\lambda/\lambda_0)$ according to the formula

$$P_{min}(\lambda / \lambda_0) = a + b/R\ (\lambda / \lambda_0),$$

where $a + b = 1$, and a takes fairly close, but different values for individual asteroids. Thus, the only reason causing the change in $P_{min}(\lambda)$ with the wavelength is the spectral variations of the color index $R(\lambda/\lambda_0)$ and not the spectral albedo $A(\lambda)$. It follows that the spectral analogue of Umov’s law “the greater the polarization degree, the less albedo” may not be satisfied for individual asteroids, in any case, in the region of phase angles at which a negative degree of polarization is observed.

2.6. Photopolarimetric asteroid system

Applying the approximating formula [8] to the polarimetric observations of asteroids collected in the corresponding databases, we calculated 153 phase polarization curves in different spectral ranges for the asteroids of various optical types. At the next stage of the work, we undertook a search for the relationship between the photometric and polarimetric parameters that determine the phase functions of brightness and the polarization degree of asteroids. Statistically significant relationships were found between the phase coefficient b and the parameters of the polarimetric function. In particular, we confirmed the relationship between b and the maximum degree of negative polarization $|P_{min}|$, which was first discovered by us for asteroids in 1983 [21]. New relationships were also found between b and the remaining parameters of the negative branch of the polarization curve, namely, the inversion phase angle α_i, the phase angle α_{min} at which the minimum polarization P_{min} occurs, and the slope parameter h of the polarization curve at the inversion angle. Moreover, it is possible to determine the spherical albedo of asteroids if their phase coefficients are known [23].

So, knowing only the phase coefficient of the asteroid allows us to estimate with reasonable accuracy its geometric and spherical albedo, as well as all the parameters of the phase branch of negative polarization and, as a nice bonus, the diameter of the asteroid. This remarkable property of regolith of minor planets we called the photopolarimetric system of asteroids [22, 23, 24]. The optical properties of asteroid regolith, which determine the photopolarimetric system, can be summarized as follows. The lower the albedo of the rough granular surface of asteroids with a complex "open" relief, the greater the shadow density that surface irregularities cast. This in turn leads to increasing the phase coefficient, the amplitude of the negative polarization branch, and the slope parameter at the point of inversion of polarization degree.

3. Polarimetric properties of cometary atmospheres

As in the case of asteroids, polarimetric observations of comets, as a rule, do not provide the necessary coverage of phase angles in order to calculate with good accuracy the parameters of the polarization phase curve. From the comet polarimetric catalog presented on the Planet Data System website (NASA PDS), we selected 20 comets with a low level of activity in order to calculate regular polarimetric curves for them using the formula [8] and the least squares method. A total of 82 polarimetric curves were calculated in different spectral bandpasses. Then we performed studies of the polarimetric properties of the gas-dust atmospheres of these comets [24, 25, 26].

3.1. Negative branch of the degree of linear polarization of comets

Using the calculated values of the polarimetric parameters h, P_{min}, α_i, α_{min} for the individual comets at different wavelengths, we found that the variations of $P_{min}(\lambda)$, $\alpha_i(\lambda)$ and $\alpha_{min}(\lambda)$ in the spectral range 3882 – 7903Å are comparable with the errors in their determination. This means that the shape of the negative branch of the comet polarization phase function weakly depends on the spectral region in which observations are made. On the contrary, the polarimetric slope h increases with the wavelength of the observations, and the correlation is statistically significant. This pattern, apparently, reflects the fact that the positive polarization of cometary atmospheres, as a rule, increases with the wavelength.

3.2. The systematization of comets in accordance with their maximum degree of polarization

The observations of most comets presented in modern databases were made at the phase angles that, as a rule, do not exceed 80° and, therefore, the position of the maximum degree of positive polarization (i.e., P_{max} and α_{max}) remains undefined. To extract more information from the source data, we selected comets with a known value of P_{max} and obtained the relationship between this parameter and the slope of the polarimetric curves $\delta P = P(50^o) – P(30^o)$ in the range of phase angles 30° - 50°:

$$P^*_{max} = 2.88\ \delta P \pm 2\%.$$

Since δP is known for all comets in our sample, we can estimate the maximum polarization for those comets that could not be observed in the desired interval of phase angles. It turned out that the deviations between P^*_{max} and extrapolated P_{max} values, which are calculated by the formula [8], lie in the range of 2-3%. That is, the approximating formula [8] is able to predict with good accuracy the value of the maximum degree of polarization, which for one reason or another was not obtained by observation.

Then we examined the problem of classifying comets by the value of P_{max} which has a long history of discussions in the literature on comet physics. This problem, in fact, boils down to two questions:

- Can the observed set of comets decay into two or more populations differing in magnitude of P_{max}?

- if the answer is yes, is this separation caused by the physical properties of the dust itself and/or the relative content of the dust component in comet atmospheres?

Considering the first question, we applied Student's *t*-criteria to test the hypothesis that the average values of the maximum degree of polarization are equal for two comet populations. We repeated this procedure twice, examining P^*_{max} values corresponding to the red and blue spectral ranges. In both cases, the value of t-statistics was significantly larger than the theoretical value of t_q at a confidence level of 0.95. Therefore, the null hypothesis of equality of mean values should be rejected with a probability of 95%.

Thus, statistical analysis leads to the conclusion that there are at least two groups of comets that differ in the parameter of the maximum degree of polarization.

3.3.The maximum degree of polarization and the dust/gas ratio in the atmospheres of the comets

The relative content of dust and gas in the shells of comets was estimated using the ratios $Af\rho/Q(H_2O)$, $Af\rho/Q(CN)$, and $Af\rho/Q(C_2)$. The parameter $Af\rho$ estimates the rate of dust production by the nucleus into the cometary shell (A is the albedo of dust particles, f is the fraction of the aperture of the telescope filled with cometary particles, ρ is the angular radius of the aperture), $Q(\cdot)$ is the production rate of a given gas molecule, which is calculated from measurements in the emission bands of this molecule. These parameters were taken from spectrophotometric and broadband photometric catalogs of comets available in the Planetary Data System.

A comparison of P^*_{max} obtained both in the CN and C_2 emission bands and in the continuum of cometary spectra with the $Af\rho/Q(\cdot)$ ratios for water, cyan, and diatomic carbon molecules leads to statistically significant correlations. Moreover, the larger the dust/gas ratio in comets, the greater their maximum degree of polarization.

Thus, we come to the following conclusions:

- such a basic characteristic of cometary shells as the dust/gas ratio makes a significant contribution to changing the degree of positive polarization of comets;
- the dust/gas ratio may be one of the factors that determines the separation of comets into two groups with high and low positive polarization;
- in order to correctly interpret the physical properties of cometary dust, the polarimetric effect of resonance fluorescence of gas molecules should be completely excluded from the phase curve of the degree of polarization.

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