THE DIVERSITY OF THE OPPOSITION EFFECT AMONG ASTEROIDS

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INTRODUCTION

The sharp increase in asteroid brightness near opposition called the opposition effect (OE) was firstly discovered by Gehrels (1956) for the S-type asteroid 20 Massalia. Further observations proved that it is a general phenomenon for asteroids. At first the opposition effect was considered to be very similar among different types of asteroids (Gehrels and Taylor, 1977; Gehrels and Tedesco, 1979). Scaltriti and Zappala (1980) performed a thorough analysis of phase curves of 26 asteroids. They concluded that similarity of the opposition effect amplitudes among asteroids is independent of their albedo. Later special observational campaigns were organized to enlarge the observational data set (*e.g.*, Harris *et al.*, 1989; Shevchenko *et al.*, 1997). Harris *et al.* (1989) discovered a very sharp and narrow opposition effect peak for the high-albedo E-type asteroids. On the other hand, some low albedo asteroids show an almost linear magnitude-phase dependence down to a phase angle of 2 deg (French, 1987; Harris and Young, 1989; Shevchenko *et al.*, 1996). The purpose of the present work is to summarize and critically analyze the available observational data on the asteroid opposition effect.

MEAN VALUES OF THE ASTEROID OPPOSITION EFFECT

For this analysis we have chosen the asteroid magnitude-phase curves which have a good phase angle coverage and small scattering within the observational data. At present there are 37 asteroids observed at least three times at small phase angles including subdegree range. All the data were obtained in the V band and were reduced to the standard geometry of observations if it was necessary. The absolute magnitudes were taken at the primary maximum of an asteroid lightcurve which is known to be slightly influenced by the asteroid shape elongation (Surdej and Surdej, 1978). Although the number of asteroids under consideration has not greatly changed as compared to previous analyses of asteroid phase curves, the quality of the data considered here has essentially improved.

To provide quantitative estimates of observed differences among phase curves for asteroids of different composition it is important to be clear about the taken definition of OE. There are two different conventions typically used to define the OE: the absolute increase in brightness, *e.g.*, I(1°)/I(7°), or the relative excess above the extrapolation of the linear part of phase curve. In the second definition the OE is considered as a separate phenomenon caused by a mechanism distinct from the rest of the phase curve. We will use both definitions of the OE and it will be shown below that our conclusions do not depend on a chosen OE definition.

Table 1 summarizes the mean values of opposition effect parameters and their standard deviations calculated for different asteroid types.

Table 1: Mean values of opposition effect parameters for different asteroid types

Type	N	Geometric albedo ($p_{\rm v}$)	OE amplitude at $\alpha = 0.^\circ 3$ (mag)	Ratio of intensities: I(0°.3)/I(5°)	Angle of the OE beginning (deg)
P	5	0.04 ± 0.01	0.10 ± 0.04	1.30 ± 0.03	3.0 ± 1.3
C	8	0.07 ± 0.01	0.16 ± 0.05	1.34 ± 0.05	4.4 ± 1.2
M	7	0.16 ± 0.04	0.34 ± 0.04	1.45 ± 0.04	5.9 ± 0.7
S	10	0.21 ± 0.04	0.35 ± 0.04	1.44 ± 0.03	5.3 ± 1.2
E	4	0.51 ± 0.03	0.23 ± 0.03	1.28 ± 0.03	3.2 ± 1.2

The first two columns of the table gives asteroid compositional types according to Tholen (1989) and the number of asteroids taken inside each type. The mean albedo was calculated using the IRAS albedo database

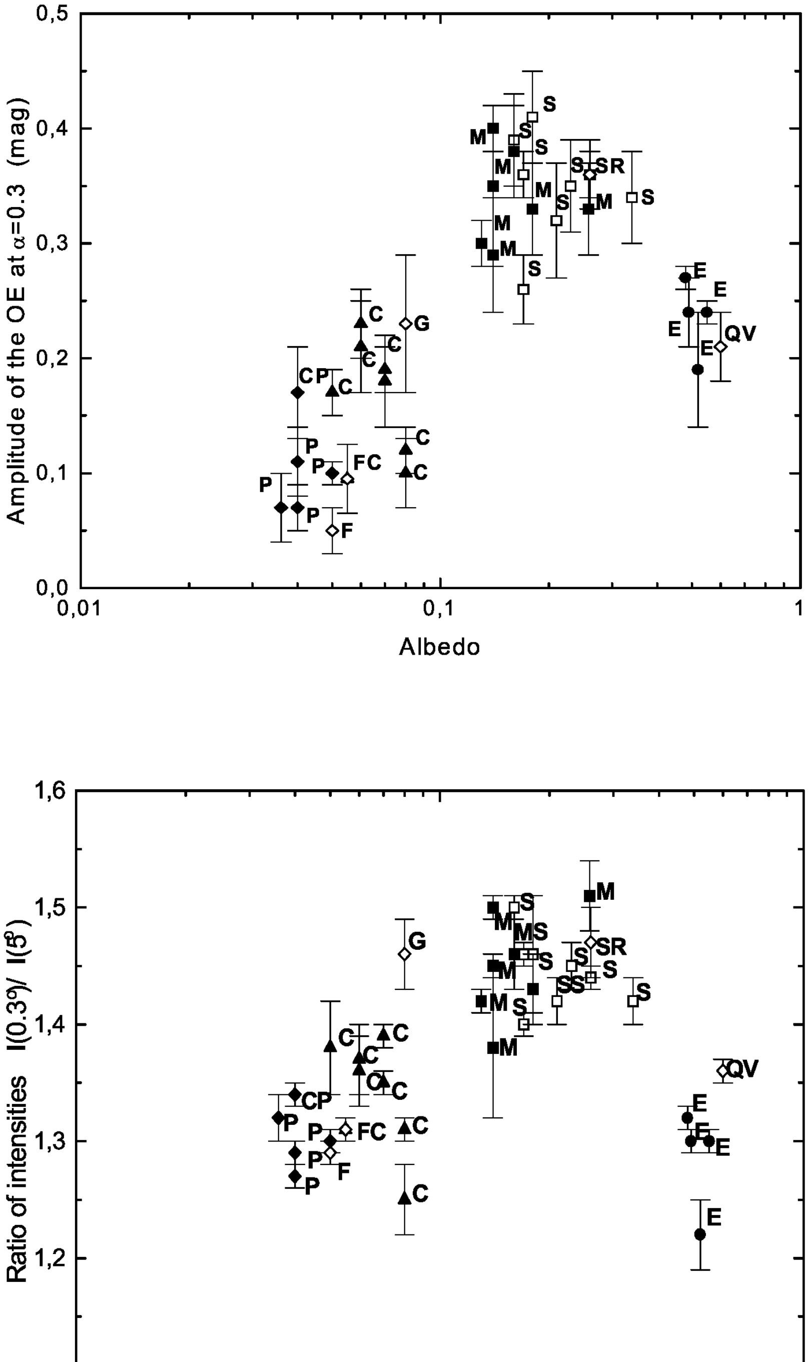

Figure 1: Dependences of the opposition effect calculated as the excess in magnitude at $\alpha = 0\overset{\circ}{.}3$ relatively to the extrapolated linear part of phase curve (top) and as the ratio of intensity at $\alpha = 0\overset{\circ}{.}3$ to that at $\alpha = 5^\circ$ (bottom) versus albedo for asteroids of various types

(Tedesco *et al.*, 1992). The OE amplitude was measured at a phase angle of 0.3 deg relative to the extrapolation of the linear part of magnitude-phase curve. The ratio of intensity at 0.3 deg of phase angle measured relative to that at 5 deg characterizes the absolute increase in asteroid brightness near opposition. The mean value of the angle at which non-linear increase in magnitude-phase dependence begins was calculated using the composite magnitude-phase curves for each asteroid type. We consider this angle as an important characteristic of the opposition effect phenomenon. Unfortunately, the value of the angle is often uncertain for an individual asteroid because of poor phase angle coverage in the range of interest.

We have chosen 0.3 deg as the phase angle at which the value of the OE amplitude was determined for two reasons: 1) very few observations of asteroid brightness are available at smaller phase angles ($\alpha = 0^\circ\!.3$ is the mean minimal phase angle of observations for the considered data set). The extrapolation depends strongly on the assumed approximating function; 2) the influence of the finite angular size of the solar disk (*e.g.*, Shkuratov, 1991) which is difficult to take into account based on available observational data.

The diversity of phase curves are clearly seen for the main asteroid types. The OE amplitudes differ for both absolute and relative measurements. Asteroids of the S and M types show the largest values of the OE amplitude. Note that differences in the OE amplitude within a particular type are relatively small, not exceeding 0.1 mag. For most types the differences between individual phase curves are on the order of the observational scatter. For the C-type asteroids there are systematic differences in the opposition effect steepness for phase curves of different low-albedo asteroids.

The angle at which non-linear increase of a magnitude-phase dependence begins also varies among asteroid types. The largest angles of the OE beginning typically occur for the M and S types which have albedos in the range of 0.1–0.3. It decreases both for high albedo E type and for low albedo C and P types. For some of them the magnitude-phase dependence remains linear down to 2–3 deg. For our entire data set, the mean value of the angle of OE beginning is 4.6 deg. This result is rather unexpected since previously it was considered that the OE of asteroids begins at phase angles of 7–9 deg (Scaltriti and Zappala, 1980).

ALBEDO DEPENDENCE OF OPPOSITION EFFECT AMPLITUDE

Understanding of the opposition effect phenomena of atmosphereless bodies has considerably improved last decade. Now it is obviously that there are two main mechanisms; namely shadow hiding and coherent backscatter causing the OE phenomena. Detailed descriptions of the OE mechanisms can be found in Hapke (1993), Muinonen (1993), and Shkuratov (1994). Mishchenko and Dlugach (1993) demonstrated quantitatively that the coherent backscattering can explain observed narrow opposition effect for the E-type asteroids. Available theoretical models give a number of predictions. In particular, the dependence of OE amplitude on albedo is of a great importance. According to Hapke (1993) the coherent backscatter effect can be distinguished observationally from the shadow-hiding effect with a help of the OE amplitude dependence on albedo.

Dependence of the OE amplitude on albedo for asteroids of various types is shown in Fig. 1. The amplitude of OE clearly varies with asteroid albedo in a non-monotonic way. Values of the OE amplitude defined both as absolute and as relative increases in magnitude show a similar dependence on albedo. The amplitude of the OE decreases both for dark and high albedo asteroids. The largest amplitude occurs with moderate albedo asteroids (about 20% of albedo). According to Hapke (1993) the contribution of the shadow-hiding effect decreases as albedo increases while that for coherent-backscatter increases as albedo increases. If Hapke's conclusion is true then the observed non-monotonic dependence of the OE amplitude on albedo cannot be explained by a single mechanism.

CONCLUSIONS

The amplitude and width of OE depends on asteroid albedo in a non-monotonic way with the maximum for the moderate-albedo asteroids. Relative to this maximum, the amplitude of the OE decreases both for low and high albedo asteroids, which can be caused by combined influence of both shadow-hiding and coherent-backscatter mechanisms.

Acknowledgements. This study was supported by Ukrainian foundation of fundamental science and technology (grant N 2.4/314).

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