OPPOSITION EFFECT OF KUIPER BELT OBJECTS: PRELIMINARY ESTIMATIONS

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Abstract. Information on the surface structure of the Kuiper Belt objects can be obtained from studies of their opposition brightening. Although KBOs are observed at a very limited phase angle range they represent a unique opportunity to study the backscattering phenomenon down almost to zero phase angle. Preliminary estimations of the opposition effect amplitude and width based on composite phase curves of four KBOs and two Centaurs showed the existence of a very narrow opposition surge of about 0.1–0.2 mag at phase angles less than 0.1–0.2 deg. It may indicate a high porosity of the KBOs regoliths. Further observations are needed to confirm this phenomenon.

1. Introduction

The Kuiper Belt Objects may be observed only at a very limited phase angle range (usually less than 2 deg) where the opposition effect should play a dominant role. It is a common phenomenon inherent for the Moon, asteroids, and satellites of the major planets which is characterized by non-linear increase in surface brightness as the phase angle decreases to zero. The amplitude and width of the opposition effect depend on physical characteristics of surfaces, the width varying typically from 10 deg to less than 1 deg. Two main physical mechanisms, namely, the shadow-hiding and coherent backscatter enhancement, are considered to be responsible for the opposition effect. Narrow opposition surges observed for high albedo surfaces are usually explained by the coherent backscatter mechanism that is contributed with multiple light scattering (e.g., Mishchenko and Dlugach, 1993). Recently a noticeable narrow opposition surge at phase angles smaller than 0.6 deg was found for the dark asteroid 419 Aurelia with albedo of 0.05 (Belskaya et al., 2002).

The first tentative measurements of a few KBOs (Sheppard and Jewitt, 2002; Schaefer and Rabinowitz, 2002) have shown almost linear and fairly steep phase curves in the range of phase angles from 0.2 to 2 deg. The similar steep slope was

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found for Centaurs (Bauer et al., 2002, 2003). The question remains whether there is the sharp opposition surge in brightness for KBOs at smaller phase angles that has not been observed yet because of its narrowness.

2. Observational Data

Available observational data obtained by different authors for the same Kuiper belt objects have been collected and analyzed. An extraction of their phase curves was possible only when their brightness variations due to rotation were known or negligible. Table I gives a list of objects, for which observations of different authors are in a good agreement within observational errors and have sufficient phase angle coverage to make a conclusion about phase curve behavior. It contains the name of object, its orbital type, estimated diameters, albedos, phase angle range of observations, the absolute magnitude in the R band R(1,0) and phase slope obtained by linear approximation of phase curves at phase angles larger than 0.2 deg, and finally references for original observational data.

For three objects, 31824 (1999 UG_5), 38628 (2000 EB_{173}) and 40314 (1999 KR_{16}), composite phase curves practically do not extend the phase angle range and only confirm the previously made conclusions about steep linear phase curves (Sheppard and Jewitt, 2002). For other three objects, 15789 (1993 SC), 20000 Varuna and 10370 Hylonome, observations are available down to extremely small phase angles (0.1 deg and less). Composite magnitude phase curves in the R band for these objects are given in Figure 1. They reveal very narrow non-linear increasing in magnitudes of about 0.1–0.2 mag at phase angles less than 0.1 deg.

Neglecting the phase effects can lead to overestimating of lightcurve amplitudes as in the case of 1993 SC. Williams et al. (1995) suggested the amplitude of 0.5 mag, which was not supported by further observations of this object that give the upper limit for the amplitude of 0.12 mag (Tegler et al., 1997). The disagreement in brightness variations can be explained by extremely low phase angle observations made by Williams et al. (1995). They observed the object in phase angle range of 0.03–0.12 deg, where brightness increasing due to the opposition effect could reach considerable values and should be taken in account.

3. Discussion

Composite phase curves of two KBOs and one Centaurs gave first evidence on existence of very narrow opposition surge of about 0.1–0.2 mag for these objects. Its width is less than 0.2 deg, which seems to be the narrowest one ever observed for Solar System bodies. For two of the considered objects there are albedo estimates (see Table I) varied from 0.03 to 0.07. Important questions arise:

- can the coherent backscattering contribute to such dark surfaces where multiple scattering should be negligible?

TABLE I

KBOs and Centaurs with measured phase slopes.

Object	D(km)	Albedo	Phase range (deg)	R(1,0) (mag)	Phase slope (mag/deg)	References
10370 Hylonome	30		0.1–3.0	9.12	0.104	Luu and Jewitt 1996
(Centaur)				±0.04	±0.023	Green et al., 1997
						Magnusson et al., 1998
						Bauer et al., 2003
31824 1999 UG_5	20		1.3–7.2	9.84	0.084	Bauer et al., 2003
(Centaur)				±0.08	±0.004	Gutierrez et al., 2001
						Peixinho et al., 2001
15789 1993 SC	328⋆	0.022⋆	0.03–1.4	6.63	0.094	Williams et al., 1995
(Classical)				±0.03	±0.031	Luu and Jewitt, 1996
						Jewitt and Luu, 2001
						Tegler et al., 1997
20000 Varuna	900⋆⋆	0.07⋆⋆	0.03–2.0	3.31	0.145	Jewitt et al., 2001
(Classical)	1060⋆⋆⋆	0.038⋆⋆⋆		±0.02	±0.008	Jewitt and Sheppard, 2002
						Doressoundiram et al., 2002
						Lellouch et al., 2002
38628 2000 EB_{173}	400		0.3–1.9	4.43	0.123	Shaefer and Rabinowitcz, 2002
(Plutino)				±0.02	±0.009	Sheppard and Jewitt, 2002
						Doressoundiram et al., 2001
40314 1999 KR_{16}	400		0.16–1.3	5.37	0.140	Sheppard and Jewitt, 2002
(Plutino)				±0.02	±0.016	Trujillo and Brown, 2002

[1]Thomas et al., 2000.
[2]Jewitt et al., 2001.
[3]Lellouch et al., 2002.

– what constraints could be put on physical characteristics of such surfaces?

The answers can be given with theoretical and laboratory modeling. Thus laboratory polarimetric measurements of carbon soot (albedo is about 2%) revealed the negative polarization at very small phase angles that definitely demonstrates importance of multiple scattering in such a dark surface (Shkuratov et al., 2002). This is in a good agreement with results of computer simulations of multiple scattering in extremely dark powdered surfaces (Zubko et al., 2001). To compromise the multiple scattering availability with low surface albedo an assumption can be made about very prominent forward scattering of single particles of the KBOs regoliths. In its turn that can be related to the very fluffy structure ('fairy castles') of the KBOs surfaces as well as to low refractive index of the regolith's material (it is characteristic for organic matter). This does not contradict the laboratory

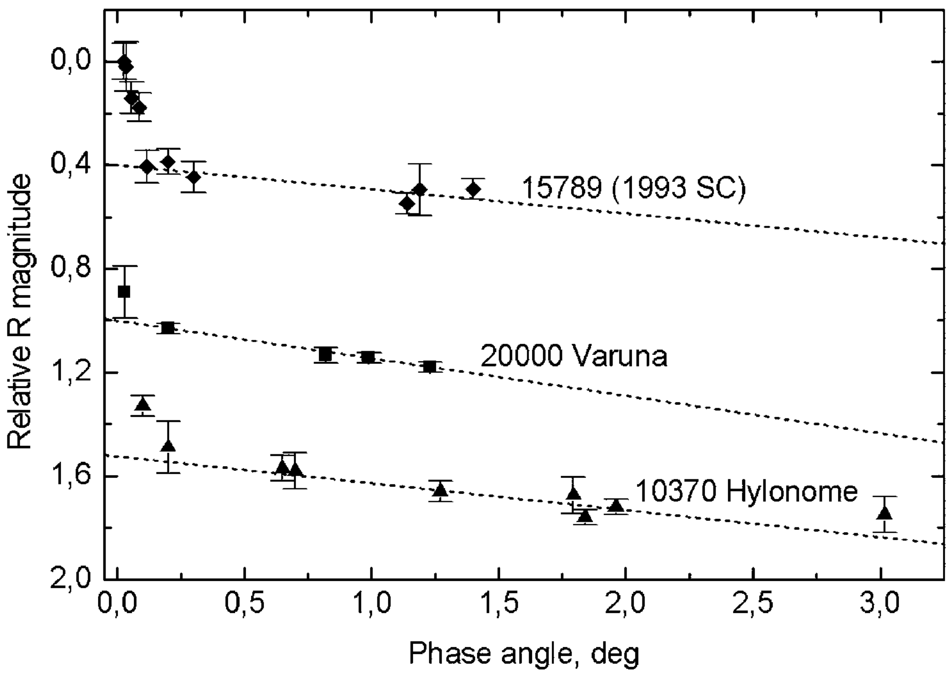

Figure 1. Composite phase curves of KBOs 15789 (1993 SC) and 20000 Varuna, and Centaur 10370 Hylonome.

simulations of Smythe et al. (2002), who revealed multiple scattering in a dark material (boron carbide) and supposed that it is due to the unique shape of particles composing the samples. The assumption about high porosity of the KBOs regoliths is in agreement with the fact that the coherent backscatter opposition surges are so narrow.

Another interesting feature of phase curves of KBOs and Centaurs is their steep linear slope. The mean linear phase coefficient calculated in the phase angle range from 0.2 to 2 deg for the composite phase curve is 0.14 ± 0.02 mag/deg. The slope of the linear part of phase curves where the shadow-hiding effect gives the major contribution (e.g., Hapke, 1993) correlates mainly with surface albedo and almost coincides with similar albedo surfaces. The measured phase slopes of KBOs are considerably larger as compared to linear phase coefficients of other Solar system bodies not exceeding 0.05 mag/deg. It can be explained by the existence of a broad opposition effect in the phase curves of KBOs, which we cannot distinguish from linear dependence because of the very limited phase angle range. However, observations in the larger phase angle range of 1.3–7.2 deg for Centaur 31824 (1999 UG_5) are also characterized by a steep linear dependence with the phase coefficient of 0.08 mag/deg. It could be an indication of a different structure of the top surface layer of these objects compared to asteroids and atmosphereless satellites. This can be considered in favor of the assumption of more fluffy regoliths of KBOs compared to asteroid surfaces.

Our preliminary estimations of the opposition effect for a few KBOs and Centaurs have shown that its value is not negligible and should be taken into account to reduce observations to similar or zero phase angles. For observations at phase angles of 0.2–2 deg the linear phase curve with phase coefficient of 0.14 mag/deg in the R band is the best approximation of phase effect according to available data (see also Sheppard and Jewitt, 2002). At phase angles close to zero (less than 0.2–0.1 deg) non-linear behavior of magnitude is anticipated. All data obtained at these extremely small phase angles should be carefully analyzed to avoid phase effects.

4. Future Work

Further observations of the KBOs are needed to confirm the preliminary conclusions on their opposition effect. To investigate the amplitude and width of the opposition surge for these objects, detailed observations of selected KBOs and Centaurs should be carried out down to extremely small phase angles (less than 0.1 deg), where the non-linear opposition surge is expected. We plan laboratory photometric measurements of dark surfaces at very small phase angles to interpret the phase curves of Kuiper belt objects and Centaurs.

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