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Deflection of Hazardous Near-Earth Objects by High Concentrated Sunlight and Adequate Design of Optical Collector

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Abstract Some detailed astronomical and applied aspects deflection of hazardous near-Earth objects (NEO) by direct high concentrated sunlight, causing intensive local ablation of their surfaces, are considered. The major requirements to solar concentrating optics within a single collector (a large mirror) approach, along with the asteroid properties being most substantial in achieving the predetermined effect for the period less than a year (mid-thrust action), are discussed. Such a hastened strategy may become topical in the case of late detection of potential danger, and also, if required, in providing the possibility for some additional action. It is also more acceptable in the public perception and keeping the peace for mankind rather than a long-run expectation of the incorrigible deflection resulting shortly ahead of the predicted hazard. The conventional concave reflectors have been graved to be practically inapplicable within the high concentrating geometry. This is primarily because of the dramatic spread of their focal spots at needful inclinations of optical axis from the direction toward the Sun, as well as of problematic use of the secondary optics. An alternative design of a mirrored ring-array collector is presented (as a tested and approved point-focus version of innovative reflective lenses for sunlight concentration within this approach), and comparative analysis was made. The assessment argues in favor of such a type of high-aperture optics having more capabilities than conventional devices. Mainly, this is because of the underside position (as respects the entrance aperture) of its focal area that allows avoidance of target shadowing the reflecting surfaces and minimizes their coating by the ejected debris. By using the modern asteroids database, some key estimations have been obtained. The surface irradiance around 4–5 MW/m^2 (average across the focal spot concentration level $\sim 5 \times 10^3$) for the ring-array collector size ~ 0.5 of asteroid diameter might suffice to deflect a 0.5-km-diameter NEO during several months. For the larger diameter NEOs, to 1.3–2.2 km, the required collector sizes are about the asteroid diameters, and they are even greater for more massive objects.

Keywords Hazardous near-Earth objects · Deflection by high concentrated sunlight · Asteroid properties · Mid-thrust action · Ring-array concentrating collector

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1 Introduction

The present discussions on avoiding the hazardous impact of near-Earth objects (NEOs—actually being asteroids and less probably—comets) on our planet contain not only the fundamental problems, but also more practical and detailed aspects—see, for example, McInnes (2004), Lu and Love (2005), Fargion (2008), Vasile and Maddock (2010), Prado et al. (2011) and Lomakin et al. (2011). Unlike instantaneous (explosive high-thrust) and environmentally risky methods of NEO destruction or deflection which were proposed in the early stage of this trend development, the most considered alternative approaches to solving this problem imply using relatively low-power modes (low-thrust actions). These modes allow the achievement of a more controllable process of deflection, though they require too long periods for their eventual fulfillment. The number of existing NEOs greatly exceeds that of those already discovered (Bottke et al. 2002; Chapman 2008), though most NEOs larger than 1 km in diameter have been already cataloged. Thus, the cases of late detection of potential danger cannot be excluded in future. Hence, humanity can suddenly fall into a situation of shortage of time for preparations and implementation of a planetary-scale protective mission. Besides, shortening of the deflection process seems to be most preferable also in the case of no time deficit to avoid the hazard. Really, being implemented long before the possible impact, the orbit deviation will be continuously observable and further predictable. Therefore, the deflection can be repeatedly or additionally performed in case of necessity. Such a strategy will be more tolerant as respects keeping the peace of humans worldwide in contrast to a long-run expectation of the incorrigible "last chance" deflection (though successful but not publicly perceived and analyzed in detail) shortly ahead of the predicted hazard. These arguments bring to the forefront the minimization of thrust period as a priority parameter for the mitigation method.

Multi-criteria appraisal, and the more so the systems analysis of the problem, lead to the conclusion that an energy-saving and simultaneously powerful and environmentally friendly method of NEO mitigation is the deflection by the direct effect of concentrated solar radiation. This method was described and analyzed in a variety of papers (Melosh and Nemchinov 1993; Kahle et al. 2006a; Maddock et al. 2007; Sanchez Cuartielles et al. 2007; Vasile 2009; Gong et al. 2011). From the technical point of view, the facility required for this, except that mounted on spacecraft, includes the large-scale power optics, that is, a solar concentrating collector which under certain conditions may cause a strongly thrusting jet consisting of the ablated matter of an asteroid or comet nucleus. The total power of the concentrated flux of the sunlight is proportional to the squared collector's working area sizes, and the focal irradiance is proportional to the concentration ratio which, in turn, is inversely proportional to the squared collector's focal length. Therefore, by the use of a sufficient quality and size collector, which is located not far from a target, the time-saving (but non-instantaneous) predetermined orbit deviation is probable even for a large- and regular-shape NEO upon which the induced low-intensive sublimation and classic Yarkovsky effect exert minimal influence. This mode, along with estimating the deflection periods, in particular, those less than 1 year, was introduced for the large asteroids in a basic concept proposed by Melosh and Nemchinov (1993). Here, it is referred to as a mid-thrust action. Further development of this approach demands a detailed comparison of suitable collectors along with the NEO's properties, as well as a search for optical alternatives.

In this paper, we critically analyze the conventional light-concentrating devices aimed at local irradiance maximization of a real NEO target. Also, the tested and approved alternative optical design of a possible large-scale solar collector, which can be more capable of providing the irradiance of asteroid a surface resulting in mid-thrust NEO mitigation, is presented and discussed.

2 Requirements to Solar Concentrating Optics and Properties of NEO Targets

Below, we will focus upon a single collector concept (large-scale solar concentrating optics), leaving out of discussion the problems of mutual NEO and spacecraft's orbital dynamics which were analyzed in several papers, for example, Kahle et al. (2006b), Sanchez Cuartielles et al. (2007), Vasile (2009), and Vasile and Maddock (2010). The concentrating solar collectors of various scales, practically used now for thermal and other applications in solar energy technologies, are entirely based on the two types of design: (a) reflecting systems with a parabolic or some other kinds of concave profile of mirrored surface generatrix and (b) Fresnel lenses—see, for example, the survey in Tiwari (2000). Moreover, in the size range essentially surpassing one meter, the continuous and tessellated point-focus parabolic dishes still remain an exclusive type of optical device for achieving high target temperature. This is mainly due to the fundamental non-competitiveness of the large refractive optics, just like with the situation occurred in telescope development.

Theoretically, the concentration ratio of an "ideal" parabolic dish may reach dozens of thousand suns, though in practice, for large collectors it varies within several hundred to several thousand suns on the average across a focal spot. It will be observed that the adequate indication of the concentrating solar collector total power and efficiency is just the average across a focal spot value. Peak concentration (which, as a rule, significantly exceeds the average one and localizes just in the spot center) is not entirely characterized by the total collector heating capacity. This is especially true for the case if the local zone of maximum target irradiance is small as against the focal spot total size. Now, the closest collector prototypes for the NEO deflection are less common systems for applying the highest temperatures by concentrated solar radiation—solar furnaces, see, for example, Bortz et al. (1995). These are sufficiently large devices (their working area sizes making from several to dozens of meters) some of which being built about half a century ago. In particular, in the furnaces of a direct incidence type, the concentrating collectors are themselves directed toward the Sun. To solve, here, the discussed problems aiming at mid-thrust mitigation of large NEOs, the point-focus collector scales, those almost reached in the ground-based high concentrating solar technology, should apparently be additionally increased at least by several times. Exceptions are well known, and most scale point-focus constructions—the so-called solar towers for electricity generation whose concentrators creating somewhat smaller focal irradiance onto a single target—consist of a large set of tracking heliostats making together the huge adaptive Fresnel mirrors.

Starting with the pioneer paper of Melosh and Nemchinov (1993), for the hazard avoidable mid-thrust action, the focal surface irradiance values have been assumed to be about several MW/m^2 and greater that corresponds to the concentration power exceeding one thousand suns. Such values were also proved experimentally by the appropriate material pyrolysis in the solar furnace (Sauerborn et al. 2004). Achieving that high performance imposes rigid requirements not only to the shape and quality of a space-borne reflective surface, but also to its mutual location and orientation within the "source collector target" system. In particular, the collector reflecting surface should have a paraboloidal shape with small deviation from "perfection" (or "ideal" shape) and relatively short focal distance. In this paper, we are not dealing with some specific problems relating to maintaining the optically sufficient shape of continuous surface of that large area, as well as with the focus alignment in space.

Here, it is worthy of note that even an "ideal" conventional mirrored device is not free from several principal limitations within the geometry which requires solution to the problem under consideration. A parabolic dish is a retro-reflective device meaning that its focal area is located between the mirror and source. Obviously, such a collector must operate in space where the target (most likely, larger than the collector size or, at least, comparable) is located between the source (Sun) and the reflector proper. This fact creates the problem of blocking, at least essential part of the incident sunlight, by the NEO. Within a single-mirror concept, while preserving the high concentration level, any improvement of this location is practically impossible. Actually, an attempt to avoid shadowing by the change of mutual location or orientation of the collector will strongly reduce its concentrating ability. This is due to the dramatic spreading of a focal spot by coma aberration even at relatively small inclination of collector's optical axis to the incident sunrays. This restricting effect to the focal spot size and shape, owes to the axial misalignment of parabolic dish (optimized by concentrating ability and target surface orientation) obtained through computer simulation, is shown in Fig. 1.

The quantitative analysis also shows that such significant features as irradiance homogeneity and its peak value within a spreading focal spot sharply decrease. A spherical mirror has a more negative effect on axis misalignment. And eventually, the use of a generally known collector at its axis inclinations to the incident sunrays up to several degrees of arc and, moreover, to dozens of these leads to suppression of its high concentrating ability which is a key for intensive local overheating of asteroid surface. For the collector sizes smaller than the NEO's diameter and at large inclinations to the Sun (i.e., with low sunlight concentration), this collector will lose by thrust efficiency even to an ordinary solar sail which in turn is much less effective than the ejected matter (Melosh and Nemchinov 1993; Fargion 2008). Significant reduction in irradiance arises also if the periphery (off-axis) part of a very large parabolic dish is used because its working area is reduced, whereas its focal distance remains the same. Real proportions of the target and conventional collector sizes do not allow for an effective use of a large tracking flat-plate heliostat for pre-redirecting the sunrays, although this leads to significant complexity and total mass increase in the whole space system. Accordingly, for the same reason, besides plenty of tracking mirrors in solar towers, the concentrators of modern solar furnaces consist of hundreds of facets with different curvatures, capable of operation, however, only at fixed geometry due to the tracking heliostat. The similar concept of the dynamic

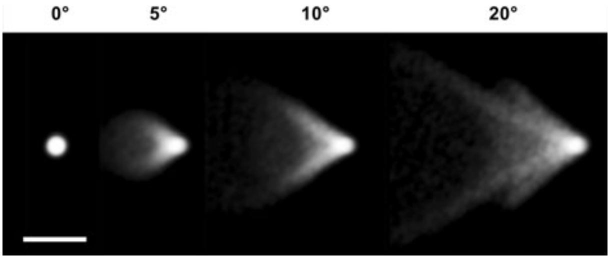

Fig. 1 Focal spots produced by an "ideal" and optimized to concentrating ability dish-parabolic collector for different angles of axial misalignments to the Sun (*angle values* are given on *top*) and keeping normal axis orientation to the target plane. The *scale line* in the *lower-left* corner corresponds to 5 % of the collector focal distance

(without heliostat) version for the NEO deflecting optics—swarm of mirrors—was proposed some time ago in Vasile (2009).

Kahle et al. (2006a) described other limitations of a single conventional concentrating collector. Among those, the most critical and first noted in Melosh and Nemchinov (1993) is the contamination of a reflective surface frontally turned by ablated debris that may lead to collector degradation. The primary mirror is exposed to the debris, if the direct incidence scheme without additional optics will be used, or the secondary one—for more complex schemes. Various contaminating, distorting, and damaging influencing factors are much more predictable for the secondary (near-focal) optics in view of its functioning as well under strong flux of sunlight. Moreover, any possible increase in the collector's distance from the target (or optical path length for the concentrated rays) by means of secondaries (lens, mirror, combined, collimating, turning or directing, including Cassegrain-like and Newton-like arrangements) leads to reduction in the focal irradiance by the square low. This is due to the fundamental physical reasons—unremovable divergence of sunrays that corresponds to a 32-min solar disk angular diameter and results in that the minimum size of a focal spot (image of solar disk for the parabolic dish and focal response for non-imaging optics) always makes about 9×10^{-3} of the focal distance. In order to keep the concentration degree at the previous level, increasing the focal distance should be accompanied by the corresponding growth of collector sizes. The listed circumstances make the use of the secondary optics for the given purpose highly problematic. An applicable and simple approach to solving the aforementioned problems within a single conventional collector's concept has been not yet found.

Now let us consider the NEO properties which are most substantial for achieving the desired ablation effect. Practically, as targets for deflecting by the concentrated solar flux, these objects are complicated enough. Being limited to consideration of a near-Earth asteroid family, whose data are continuously updated, we have to note the following. On the one hand, such a feature as the low albedo promotes quick starting of local overheat and, hence, intensive ablation. The NEOWISE data (Mainzer et al. 2011), as well as those observed with Warm Spitzer (Mueller et al. 2011), show that the NEO albedos range widely, with relative prevalence of dark objects. Here, we traditionally use the term "diameter" for asteroids meaning the average size of a body of irregular shape. Low spin rate also may refer to positive factors, especially for the large NEOs. In order to obtain a multi-parameter picture of the aforesaid factors, we have collected about 120 massive (of diameters larger than 0.1 km) NEOs with simultaneously known values of albedo, diameter, and spin rate from (Asteroid Lightcurve Data Base 2012). The result is shown in Fig. 2.

As is seen from Fig. 2, the most part of asteroids whose albedo is less or comparable with the energy losses due to absorption by a real mirrored surface (around 15–20 %) is grouped within the region of rather small spin rates. Most of large NEOs also gravitate toward this region. Such a situation can also be considered as encouraging within the discussed approach. Certainly, this limited sample is not capable of exhaustively characterizing all the set of existing NEOs with dangerous masses, but may be useful for initial estimates and the determination of construction parameters for the deflecting optics. By analogy to meteorites, the small depth for light penetration into the asteroid surface is supposed to be about 100 micron (Matloff et al. 2010) that may also be referred to positive factors. On the other hand, a vitally rough relief with scales exceeding the focal spot size as well as the high spin rate may be referred to rather inhibitory features for the implementation of the given approach with any type of optics.

If the NEO spin and aspect are not suitable for the focal spot predetermined position, a necessary deceleration or stop of spinning can be possible by timely direction of a

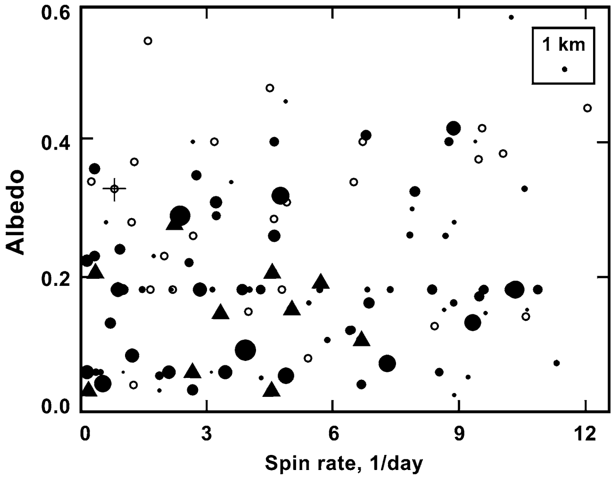

Fig. 2 Albedo versus spin rate and diameter for the cataloged near-Earth asteroids larger than 0.1 km in diameter. Within 0.7–5 km, the asteroid diameters are proportional to the sizes of the *filled circles*. Compatibility between the linear scale and diameter is shown in the *upper-right* corner. Asteroids of about 0.7-km diameter and *smaller* are indicated by the identical *blank circles* (Apophis, in addition, is *crossed*), and the largest asteroids of more than 5-km diameter are indicated by the *identical filled triangles*

concentrated beam to near-limb surface regions with their topography taken into account. As a criterion for the necessity of such an operation can be the interrelation of an irradiated surface linear velocity and the rate of quasi-equilibrium ablation process. We may assume the stable position of a focal spot resulting in the creation of a local cavity which will promote jet collimation. On the other hand, heterogeneity of regolith, and in turn some instability of its ablation together with tracking errors, will probably lead to temporary drifting of a focal spot along the NEO surface. Thus, the real irradiation mode is similar to slow spinning which, as was duly noted by Melosh and Nemchinov (1993), would serve to bring "fresh material into the heated area." Images of the 350-m near-Earth asteroid Itokawa, recently obtained with the currently highest spatial resolution, demonstrate that the fine-grained materials are generally distributed on the surface between larger particles whose diameters range from centimeters to meters (Takeuchi et al. 2010).

Parameters of a cone-like vapor jet in a model of flat surface were estimated by Kahle et al. (2006a) for a generally wide flow of escaping matter. Detailed analysis of the Halley's comet images (Keller et al. 1987) shows, however, that even under non-concentrated solar irradiation, its local active regions produced the anisotropic jet-like flows (of lower speed as against our case) with relatively collimated cores in the nucleus vicinity, whereas similar behavior does also show laser-induced plasma jets (of higher speed) obtained during the vacuum and vacuum-less ablation of planar metal targets. According to experimental results, most of ejected matter does not exhibit a tendency to large incline from the normal direction to the parent surface (Nicolai et al. 2007; Chuchman et al. 2011). In any case, further clarification of the dependence of jet collimation degree and direction versus mutual orientation of the concentrated beam and NEO surface requires, besides the theoretical modeling, making the experiments—those vacuum including. In these experiments, it is highly advisable to account for an adequate scale and approaching to the real surface features.

3 Deflection Concept with Alternative Ring-array Concentrating Collector

Ring-array concentrator (RAC) as a point-focus version of innovative reflective (refraction-less) lenses—see (Vasylyev 2002; Vasylyev and Vasylyev 2012) and references therein—allows to axially collect the sunlight and irradiate the NEO from the front (insolated) side, absolutely without shadowing by any size target. RAC is formed by an array of nested reflective elements—profiled rings (conical frusta) which are packed with the required density to be able to intercept most of sunlight striking its entrance aperture and working area. All reflective surfaces are inclined at an acute angle with respect to the optical axis. This allows the incident sunrays to pass downward through spaces between the adjacent surfaces and get collected into a small focal area below the optical system. Such a design also allows to form the focal spots with predetermined irradiance distributions and maximum concentrating ratio. In addition, the RAC's optical configuration is tolerant to relatively small (no more than an angular diameter of solar disk) optical axis misalignments (Vasylyev 2002), thus minimizing the chaotic drift of the focal spot along the target surface.

Conceptually, the RAC-type solar collector is similar to a grazing-incident X-ray telescope and may be considered as a higher aperture and pass through (with respect to the incident sunlight) optical alternative to a parabolic dish or the like devices. Now, it has been tested and approved by numerous computer simulations and small-scale prototyping, this latter having exhibited its maximum concentrating ability and adaptability to the various purposes of use. In particular, some field testing of the RAC prototypes has shown that ablation of low-albedo surfaces is achievable even at that small working area which determines the total capacity of concentrated sunlight. Fig. 3 shows the two tested examples of ring-array concentrating collector with different number of reflecting elements, sizes up to 0.5 m, and average concentration ratio of about several thousand suns. To better explain the geometry of the RAC, these prototypes are shown together with the ray-trace diagram illustrating the operating principle of their optical schemes.

Figure 4 represents the prospective scheme of asteroid deflection by means of the discussed type of solar collector. Jet alignment corresponds here to a radial traction

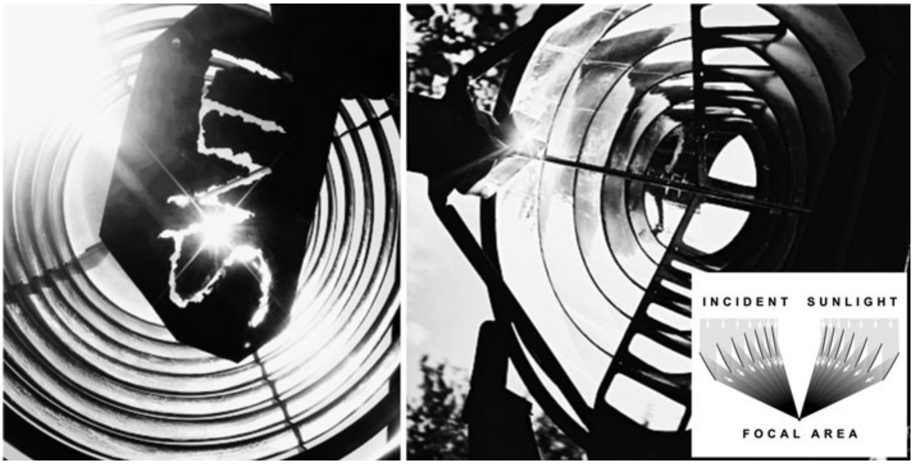

Fig. 3 Prototypes of ring-array solar concentrating collectors under field testing. An example of ray-trace diagram illustrating the operating principle of optical scheme of the RAC is shown in the *lower-right* corner

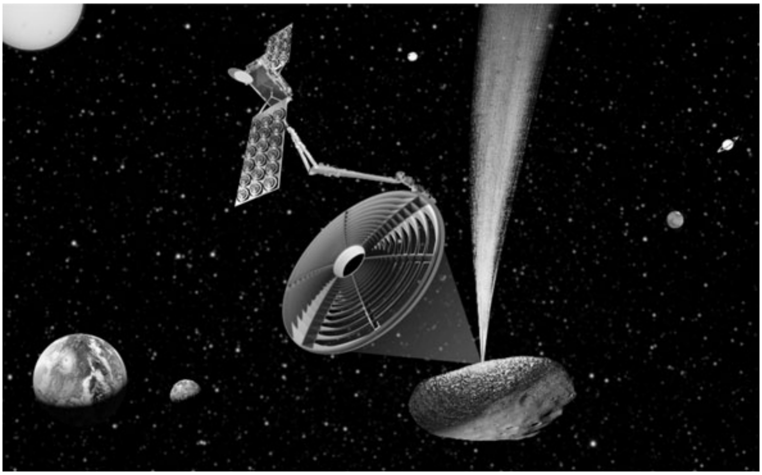

Fig. 4 View of possible scheme for asteroid deflection by the ring-array concentrating collector during the induction of a radial traction impulse. For descriptive reason, only collimated core of a jet-like flow is shown, while mutual scales partially are not kept

impulse (location of ablating area near the subsolar meridian) which is more effective for a planetary close approach prior to the collision (Kahle et al. 2006b). In order to increase a tangential component of traction impulse which is optimal for the phases of unperturbed two-body motion (Kahle et al. 2006b), the area can be moved closer to the asteroid limb. As is seen from the imaginary modification of Fig. 4, a possible application of a flat-plate heliostat for the like reasons poses no shadowing problem for a working area of concentrating collector, whereas keeping its axial orientation even to the redirected flux of sunlight.

Assumption can be made that underside orientation of mirrors relative to the most active part of vapor jet, along with the device transparency for a gas flow, will promote to reduction in the discussed coating of the reflecting surfaces of rings by the ejected debris. In addition, a protective screen which is made as a light and thin truncated cone (not shown in the Fig. 4) and mounted on the outer perimeter of the collector along the concentrated flux boundary (shown by the scattered sunlight) may further minimize this negative factor. Deviation of speed vectors of the jet particles from the collector direction can also be promoted by a non-perpendicularity of a local regolith surface to the collector optical axis.

Another scheme will be more adequate in case of necessity to direct a jet core mainly along the collector optical axis. The RAC may be designed with a large aperture size-to-focal distance ratio. In turn, the collector central hole can be widened to the prospective jet section size. The resulting collector power reduction due to working area decrease will not exceed the energy losses at reflection of sunlight. Then, most of escaping matter will pass through the hole because the jet, due to a relatively short focal distance, has not yet extended enough. Otherwise, within such a scheme, an essential negative parameter (closeness to the NEO surface) becomes the advantage (possibility to direct the jet in the zone which is free from reflective elements). It is also probable that an ultralow-speed component of ablated matter may collect around the asteroid and mirrors thus forming a temporary bound cocoon which may add some all-side moving and potentially coating debris. High asteroid surface irradiance yields the ablation starting scores of times, such that this component could dissipate during the maneuver intervals. At the same time, it is obvious that we cannot fully avoid impinging of the collector by evaporated matter irrespective of any optical scheme. Therefore, special protective technologies and means, like anti-adhesive transparent coating of the reflective surfaces or multi-layer and self-removable transparent films, placed between the ablation flow and collector, should be further developed.

The evaporation process and vapor jet parameters were modelled in Kahle et al. (2006a) without detailed account of real performances and practical capacity of the collecting optics. In our analysis for the RAC-based optics (deflector), together with the recently obtained properties of near-Earth asteroids (targets), we assume the following. The total power of the RAC-type solar collector placed outside the Earth atmosphere, whose size is ~200 m and equivalent focal distance ~300 m, is about 30 MW with account for the energy losses due to real reflection and scattering on the micro-defects of mirrored surfaces. For the above-specified concentration degrees, the focal spot should be approximately 3 m in diameter. As the RAC design allows to operate in the on-axial direction toward the Sun, as well as to form a desired focal irradiance distribution by varying the shape and positioning of ring's generatrices (Vasylyev and Vasylyev 2012), we may consider it as homogeneous. The total time interval, required for overheating, melting, and further evaporation by such a spot of bare rock or surface regolith layer (to put it more precisely—sums of discrete and not mutually shaded surface fragments facing toward concentrated sunlight) whose thickness is equal to the depth of light penetration, can be estimated.

Below, only the obtained results will be presented—see the known formulas derived in Melosh and Nemchinov (1993) and Kahle et al. (2006a). Use of the average for the NEO surface thermo-physical parameters (Delbo et al. 2007; Wolters and Green 2009) and tabular data for the like materials yields the total time interval ~0.3 s. For this estimation, the comparatively low albedo and low spin rate of asteroid, as well as physical processes without the radiation energy loss in approaching the high temperatures, have been supposed. Based on the typical data for the km-sized NEOs thermal conductivity (Delbo et al. 2007), we may determine the temperature conductivity 10^{-7} m^2/s at which warming up of a ~0.3-mm-deep layer occurs during the obtained time interval. Thus, for the layer, which in order of magnitude exceeds the experimental value for the sunlight penetration and requires about 3 s to evaporate, the balance between heat penetration and evaporation rates can be achieved. This is due to the increase in a warming up interval proportionally to a squared layer thickness, whereas the time required for evaporation has a linearly proportional dependence on thickness. Therefore, we may assume the 3-s interval as an effective one to characterize the evaporation rate.

Experiments with the solar furnace which delivered concentrated solar radiation up to a peak flux of 5 MW/m^2 (i.e., comparable with our assumed average irradiance, but three orders less by energy scale—up to 22 kW) show that the lunar soil simulant samples have achieved a liquid phase in 10–20 s and reach the temperatures of 1,500–1,900 K, where the pyrolysis processes take place (Sauerborn et al. 2004). Thus, our estimations correspond to the previous models (Kahle et al. 2006a) and experimental results with the account of normalization for such key parameters as the total power and concentration ratio of sunlight. Also, the lunar regolith sample of about 1-g mass was successfully vaporized by the conventional solar concentrating collectors with smaller (~1 and ~4 m) working area sizes (Cardiff et al. 2005).

The listed experimental results and estimations show that the average focal irradiance around 4–5 MW/m^2 (concentration level ~5×10^3) is well sufficient to provide the evaporation regime which is adequate for the mid-thrust mode owing to 200-m class of the

RAC-type collector. Moreover, the above obtained interrelations of relevant parameters point to the earlier indicated in Melosh and Nemchinov (1993), Kahle et al. (2006a) possibility of inducing an adequate jet even on the spinning asteroids with their relatively small diameters and spin rates (focal spot scanning mode). For instance, if an evaporated region is localized in a mid-latitude zone of asteroid, using the criterion specified at the end of the previous section, we obtain in our case that for 1- and 5-km asteroids, the spinning lowering is not necessary if their spin rate is less than 20 and 4/days, respectively. In estimation, we have supposed that noticeable reduction in ablation will cause the focal spot shift by half of its diameter during the effective evaporation period of ~ 3 s. As appears from Fig. 2, this criterion is satisfied for the majority of investigated NEOs with dangerous masses.

At the surface irradiance of an asteroid, its light-absorbing properties will be most likely defined by the albedo only during a short initial stage. Subsequently, and especially at stopped spinning (motionless focal spot mode), they will also depend upon yet unknown optical and thermodynamic properties of escaping ablation debris. Therefore, the here-obtained estimations (just as some others existing) may be substantially modified.

Nevertheless, we may also estimate the escaping mass rate and value of jet-induced traction impulse. The average molar mass of multi-composition NEO regolith may vary widely, in particular, in dependence on a taxonomic class of asteroids. At present, only the samples of NEO surface have been investigated immediately in the laboratory—particles from asteroid Itokawa, which belong to the S-class and whose surface chemical composition is similar to that of LL5 or LL6 chondrite (Kitajima et al. 2011). Reasoning from the most abundance of the S-class asteroids among the classified NEOs (Asteroid Lightcurve Data Base 2012), we may assume the average molar mass of ablated matter ~ 0.06 kg/mol in accordance with the chemical composition of corresponding meteorites (Walton and Spray 2003). Having used the same parameters of the RAC-type concentrating collector (working area size ~ 200 m, focal spot diameter ~ 3 m) and considering all material of ablated layer as gaseous yield the escaping mass rate of about 6 kg/s and root-mean-square speed of molecules ~ 0.9 km/s.

This escaping mass rate produces the applied thrust of about 10^3 N with the account of numerical factor ~ 0.5 due to mutability of the ablation flow parameters. The gravitational attraction between the concentrator and the asteroid pulls the asteroid toward the concentrator, that is, acts in opposite direction. Application, for example, of film-inflatable technologies for constructing a RAC space variant basically allows bringing its structure to comparatively light-weight—up to several tons—one. In this case, as follows from the estimates in Lu and Love (2005), its gravitational effect on massive NEOs for a rather short mid-thrust period will be insignificant. Also, the Apophis-like and smaller asteroids will lose up to 0.3 % and more of their total mass during the ablation in the course of several months, thus creating the additional feature of orbital deviation.

In the further estimations, we will assume that about several times greater impulse is needed than that obtained to miss the Earth because of the orbital dynamics, and also because of a steady thrust not always be applied along the optimal (see above) directions. Using the Earth diameter as an “impact parameter” at the mid-thrust (or advancing) period from 4 months to 1 year yields the estimate for the critical asteroid diameter around 0.35–0.6 km for its deflection by a 200-m RAC. Accordingly, using a 500-m-diameter collector with the same concentrating ability will shift the critical diameter up to 0.65–1.1 km. For deflection of a 1.3- to 2.2-km-diameter asteroid, the collector working area is approaching to the same size and will exceed the NEO diameter for more massive targets. The proposed RAC-based concept obviously does not exclude also a long-lead time deflection case which might be achieved with a much smaller RAC, and/or work for a much larger asteroid. With taking into account the correction of such key parameters as the optical efficiency of reflectors and root-mean-square velocity of escaping matter, we may say that these interrelations correspond to estimations which can be obtained through the final formula in Melosh and Nemchinov (1993) .

The obtained values of ablation-produced thrusts are sufficient as well for the above-discussed case of essential (and thus efficient) decrease in a NEO's spin moment by high concentrated sunlight. As follows from the estimates, for the collector-to-target size ratios used in our examples, the spin period (say of 3 h) slowing down can be reached during the time interval much smaller than the characteristic one for the mid-thrust mode. Binary and "rubble pile" asteroids can be deflected by sequentially irradiating each mechanically non-interacting component. Comet nucleus, as an ice-rich target for mitigation by high concentrated sunlight, may produce the ablation jet with much larger value of traction impulse. This is due to probably much deeper light penetration along with extremely instability of ice at high temperatures in space.

We assume that in future each new hazardous NEO detected may demand adaptation of the parameters of RAC-based collector, by now designed or constructed to the last observed data. This is of particular importance if the NEO surface will have complex topography with the Itokawa-like regolith, and the expected changeability and heterogeneity of irradiation may lead to reduction in jet's thrust ability that will require some compensation by varying the collector size. In view of isolation of each reflecting element, this collector allows to change its size by adding/removing some rings without further reengineering of the basic design.

Thus, with account for the set of the design and operational advantages, the proposed RAC-type optical system and deflection concept based on it are able to provide better solution for avoiding possible hazardous impacts. Actually, many detailed aspects of the RAC-based concept, like the others proposed, face the initial stage of research and development. Therefore, some of them seem to be questionable and will be the subject of future works.

In addition, note that due to the lens-like operation, and therefore lack of any target size limitation, the RAC-based collector design may also serve the purpose of extraction resources in space, for propellant, life support, and construction materials (Abell et al. 2009; Elvis et al. 2011). In particular, it can be used for high-temperature asteroid and lunar production of water, hydrogen, oxygen, and metals by evaporation/splitting of ice and pyrolysis of regolith. Development and construction, as well as controllability in space of relevant scale and optical quality concentrating collectors, are rather complicated problems though not unachievable for modern technologies.

4 Conclusions

The NEOs, in spite of their complexity being as possible targets for deflection stimulated by high concentrated solar radiation, have their major properties allowing execution of this task in the mid-thrust mode. Using the conventional optical devices for such kind mode is problematic because they are not suitable in respect of fundamental and practical criteria. The designs of a ring-array reflective lens and RAC-based concept as a whole are free from principal restrictions within this approach to the dangerous NEOs mitigation. This argues in favor of the solar deflection mode which may become even more attractive for the implementation as such by further solution of accompanying technological problems. For the mid-thrust deflection of the NEOs with most dangerous masses, the required sizes of solar collectors should make more than half of the asteroid diameters.

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