Icarus 220 (2012) 65–73

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Radiative heating of carbonaceous near-Earth objects as a cause of thermal metamorphism for CK chondrites

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ARTICLE INFO

Article history:
Received 7 December 2011
Revised 27 March 2012
Accepted 15 April 2012
Available online 24 April 2012

Keywords:
Asteroids
Near-Earth objects
Meteorites
Solar radiation
Thermal histories

ABSTRACT

Metamorphic CK carbonaceous chondrites display matrix textures that are best explained by a transient thermal event with temperatures in the 550–950 K range and durations in the order of days to years, longer than what is commonly admitted for shock events but shorter than what is required for nuclide decay. We propose that radiative heating of small carbonaceous meteoroids with perihelia close to the Sun could account for the petrological features observed in CK chondrites. Numerical thermal modeling, using favorable known NEOs orbital parameters (perihelion distances between 0.07 and 0.15 AU) and physical properties of CV and CK chondrites (albedo in the range 0.01–0.1, 25% porosity, thermal diffusivity of 0.5–1.5 $W\,m^{-1}\,K^{-1}$), shows that radiative heating can heat carbonaceous meteoroids in the meter size range to core temperatures up to 1050 K, consistent with the metamorphic temperatures estimated for CK chondrites. Sizes of known CV and CK chondrites indicate that all these objects were small meteoroids (radii from a few cm to 2.5 m) prior to their atmospheric entry. Simulations of dynamic orbits for NEO objects suggest that there are numerous such bodies with suitable orbits and properties, even if they are only a small percentage of all NEOs. Radiative heating would be a secondary process (superimposed on parent-body processes) affecting meteoroids formed by the disruption of an initially homogeneous CV3-type parent body. Different petrologic types can be accounted for depending on the sizes and heliocentric distances of the objects in such a swarm.

1. Introduction

CK chondrites are the only group of carbonaceous chondrites (CCs) forming a metamorphic series from petrologic type 3 to type 6 (Kallemeyn et al., 1991). This metamorphic evolution is characterized by the chemical and textural equilibration of chondritic components: matrix, chondrules, and calcium–aluminum-rich inclusions (CAIs) (Geiger and Bischoff, 1991; Kallemeyn et al., 1991; Noguchi, 1993; Chaumard et al., 2009a). 92% (in number) of known CK samples are chemically equilibrated (types 4–6). Estimated metamorphic temperatures range from 550 to 1270 K (e.g. Geiger and Bischoff, 1991; Neff and Righter, 2006).

Based on mineralogy, petrology, and oxygen isotope analyses, it has been proposed that CK and CV carbonaceous chondrites form a continuous metamorphic series from a same parent body, rather than distinct groups (Greenwood et al., 2003, 2004, 2010; Devouard et al., 2006; Chaumard et al., 2009a). The similar cosmic-ray exposure age distributions for CVs and CKs (between 1 and 40 Myr) also support a common source for these groups (Scherer and Schultz, 2000). Recent paleomagnetic data on CVs give evidence that the Allende CV chondrite could be derived from the surface of a differentiated asteroid (Weiss et al., 2010; Elkins-Tanton et al., 2011; Humayun and Weiss, 2011). In this model, a continuous CV–CK series could imply that CKs come from the lower part of the undifferentiated layer at the surface of the differentiated asteroid.

A striking and ubiquitous feature of type 4–5 CK chondrites is the texture of their matrices which contain numerous micron- and nanometer-sized vesicles and inclusions and are much coarser than they are in ordinary chondrites (OCs) of the same petrological types (Kallemeyn et al., 1991; Rubin, 1992; Tomeoka et al., 2001, 2005; Ohnishi et al., 2007; Brearley, 2009). Heat sources commonly involved to explain parent-body metamorphism are the short and long-lived radionuclides decay, and the accretional or collisional residual heat (e.g. Ghosh et al., 2006; Huss et al., 2006). All these

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http://dx.doi.org/10.1016/j.icarus.2012.04.016

mechanisms imply heating over extended periods of time (several million years at temperatures up to the liquidus). CK textures, however, strongly suggest a transient high-temperature (HT) event (Kallemeyn et al., 1991). Rubin (1991), Scott et al. (1992), and Tomeoka et al. (2001, 2005) proposed that impact shock could be the cause of this transient HT event. The numerous nanometer-sized vesicles and opaque inclusions in the CK matrix olivines have been compared to silicate darkening, a phenomenon interpreted in OCs as the result of shock metamorphism (Heymann, 1967; Dodd, 1981; Kallemeyn et al., 1989; Stöffler et al., 1991). Shock veins, planar fractures, and mosaicism are other common signatures of shock that are used to determine shock stages (Stöffler et al., 1991; Scott et al., 1992). As discussed by Rubin (1991, 1992) and Scott et al. (1992), there is no correlation between petrologic types and shock stages for CK chondrites, in others terms the most metamorphosed CKs do not seem to correspond to the most shocked objects. To account for this observation, Rubin (1992) proposed that CK chondrites were shocked then annealed. Keil et al. (1997) showed that impacts cannot be the heat source for a global thermal metamorphism of parent bodies. This suggests that the metamorphism of CK chondrites may not be related (only) to shock, and that another source of heat would be needed to account for all observed features (Rubin, 1991, 1992; Tomeoka et al., 2001, 2005). This led us to seek an alternative source of heat that could produce HT events of short duration (between days and years), longer than is commonly invoked for shock (seconds) (Beck et al., 2005) but shorter than nuclide decay (several million years) (e.g. Huss et al., 2006). We investigate in this study the effect of radiative heating on carbonaceous near-Earth objects (NEOs) with perihelia close to the Sun.

Heating of bodies close to the Sun has been recently worked out for comets (Gounelle et al., 2008), and explored for meteoroids (small objects between 100 μm and 10 m across) and asteroids (Campins et al., 2009; Marchi et al., 2009; Ohtsuka et al., 2009; Čapek and Vokrouhlický, 2010; Jewitt and Li, 2010; Michel and Delbo, 2010; Delbo and Michel, 2011). However, except for a suggestion by Chaumard et al. (2009b), and for an allusion by Wilkening (1978), later discussed by Akai (1988) and Nakamura (2005) suggesting that radiative heating could heat hydrous CCs to temperatures sufficient for phyllosilicate dehydration, radiative heating has not been considered as a possible cause of global metamorphism on carbonaceous asteroids or meteoroids.

We investigated surface temperature variations and heat diffusion in depth for carbonaceous (C-type) NEOs with perihelia close to the Sun in order to check if radiative heating can be considered as a cause of thermal metamorphism for CK chondrites. Physical parameters such as thermal diffusivity and porosity are derived from values measured on meteorites. Temperature variations at the surface are computed first then heat diffusion in depth is solved numerically.

2. Methods

2.1. Thermal modeling

The lack of atmosphere at the surface of asteroids simplifies their thermal physics. A standard thermal model (STM) has been refined by several authors for the derivation of asteroids albedos and diameters from thermal infrared observations (e.g. Morrison, 1977; Morrison and Lebofsky, 1979; Lebofsky et al., 1986; Lebofsky and Spencer, 1989; Spencer et al., 1989; Lagerros, 1996; Harris and Lagerros, 2002). However, for small and fast rotating NEOs, the STM yielded inaccurate diameters. So, Harris (1998) developed the Near-Earth Asteroid Thermal model (NEATM), a simple thermal model used to derive sizes of asteroids from thermal infrared photometry or spectrophotometry. We use the same methods to calculate surface temperatures for objects with specific parameters.

Surface temperatures depend on the inclination and rotation period of the body. In order to investigate the largest range of temperatures due to multiple dynamical behaviors, we examined two different rotational cases corresponding to two distinct thermal states. First, we considered objects with a large rotation period (T_{rot}) (hours or more). There, surface temperature depends on the solar radiation input, black-body radiation, and the energy flux from thermal conduction due to the temperature gradient at the surface. Thermal balance at the surface of a smooth spherical object can be expressed as:

$$S_0(1-A)\left(\frac{d_{\mathrm{E}}}{d}\right)^2\cos(i)=\varepsilon\sigma T^4+k\frac{\partial T}{\partial z}\bigg|_{z=0} \tag{1}$$

where S_0 is the current solar constant (W m^{-2}), A the bolometric Bond albedo, d_{E} the Sun–Earth distance, d the heliocentric distance of the object, i the solar incidence angle, ε the infrared emissivity, σ the Stefan–Boltzmann constant, and k thermal conductivity (W m^{-1} K^{-1}). The solar radiation is supposed isotropic. This thermal state, defined by Eq. (1), corresponds to a non-isothermal behavior where different points at the surface have different temperatures.

Secondly, we investigated surface temperatures of objects with a small rotation period (minutes or less, depending on size) and with a complex rotation like 2008 TC3 (Scheirich et al., 2010). This NEO, that impacted the Earth on October 2008, was a tumbler (non-principal axis rotator, Pravec et al., 2005). Its inclination changed quasi randomly from one transit at perihelion to the next. This case tends to an ideal isothermal state where radiative heating from the Sun would be redistributed both longitudinally and latitudinally. The isothermal model may be more realistic in the case of meteoroids (Marchi et al., 2009). Estimation of this isothermal surface temperature is given by:

$$\frac{1}{4}S_0(1-A)\left(\frac{d_{\mathrm{E}}}{d}\right)^2=\varepsilon\sigma T^4+k\frac{\partial T}{\partial z}\bigg|_{z=0} \tag{2}$$

where the ¼ factor, the ratio of frontal to surface area for a spherical object, is the mean of cos(i) in Eq. (1). It can be noted that for a non-isothermal object, temperatures on the side facing the Sun are in radiative equilibrium, whereas temperatures on the hidden face depend on the bulk thermal inertia defined as $\Gamma=\sqrt{k\rho_{\mathrm{b}}c_{\mathrm{p}}}$, where ρ_{b} is the bulk density of the material (kg m^{-3}) and c_{p} the specific heat capacity (J kg^{-1} K^{-1}).

For heat conduction at depth, we considered a one-dimensional time-dependent model defined by:

$$\frac{\partial T}{\partial t}=\frac{k}{\rho_{\mathrm{b}}c_{\mathrm{p}}}\left(\frac{\partial^2T}{\partial z^2}\right) \tag{3}$$

Boundary conditions at the surface are given by Eq. (1) and (2), and at great depth l by:

$$\frac{\partial T(z,t)}{\partial z}\bigg|_{z=l}=0 \tag{4}$$

The heat equation was solved numerically using the implicit-scheme, finite difference method of Crank and Nicolson (1947), starting with the object at its aphelion and an homogeneous temperature of 2.7 K. Assuming zero inclination, temperatures at 100 nodes across an equatorial diameter were calculated every $\Delta t = T_{\mathrm{rot}}/90$ along up to 4 complete orbits using 3200 Phaethon and 2005 HC4 coordinates.