1. Introduction

The Milky Way Galaxy has a disk with a radius of 10 kpc and a thickness of 200 pc. Our solar system is located inside at ~8.5 kpc from its center. Many dark clouds are distributed in the disk.

A dark cloud consists of high-density (100–10,000 protons/cm³) (Goldsmith, 1987) and low-temperature (8–40 K) (Goldsmith, 1987) neutral gas. The size of dark clouds ranges ~0.2–174 pc (Dame et al., 1986; Goldsmith, 1987; Solomon et al., 1987). It has been estimated that ~135 clouds of over ~100 protons/cm² and ~16 clouds of over ~1000 protons/cm² encounter likely occur in the age of the sun (4.6 × 10⁹ years) (Talbot and Newman, 1977). Maruyama and Santosh (2008) suggested that some Earth’s dramatic environmental changes are controlled by triggers in outer the Earth, solar system, or galaxy. A number of previous studies have suggested that a nebula encounter may lead to an environmental catastrophe (Whitten et al., 1963; Ruderman, 1974; Begelman and Rees, 1976; Clark et al., 1977; Talbot and Newman, 1977; Pavlov et al., 2005a, 2005b). Kataoka et al. (2013, 2014) pointed that an encounter with a dark cloud would drive an environmental catastrophe leading to mass extinction. Solid particles from the hypothesized dark cloud would combine with the global environment of Earth, remaining in the stratosphere for at least several months or years. With a sunshield effect estimated to be as large as ~9.3 W m⁻², the dark cloud would have caused global climate cooling in the last 8 Myr of the Cretaceous period, consistent with the variations of stable isotope ratios in oxygen (Barrera and Huber, 1990; Li and Keller, 1998; Barrera and Savin, 1999; Li and Keller, 1999) and strontium (Barrera and Huber, 1990; Ingram, 1995; Sugarman et al., 1995). The resulting growth of the continental ice sheet also resulted in a regression of the sea level. The global cooling, which appears to be associated with a decrease in the diversity of fossils, eventually led to the mass extinction at the K-Pg boundary.
Through the Ocean Drilling Program (ODP), a core sample of pelagic sediment was taken at Site 886C, at a water depth of 5713.3 m in the central North Pacific (44°41.384’N, 168°14.400’W) (Fig. 2). This site has been in an area of pelagic accumulation at least since the end of the Cretaceous Period. The accumulation rate is estimated to be as low as 3 m Myr⁻¹ (Fig. 1) (Ingram, 1995). Kyte et al. (1995) measured the iridium density in the core sample of Site 886C at a depth of 0.75–72.2 m below the sea floor (mbsf) with a pelagic-sedimentation record extending from the Late Cretaceous (77.77 Ma at 71.60 mbsf) to the Late Miocene (9.8 Ma at 54.6 mbsf). The age of sediment was determined based on Sr-isotope stratigraphy below 54 mbsf of 886C (Ingram, 1995).

![Fig. 1. Relationship between iridium abundance and sedimentation speed. Whereas the thin black solid line delineates the present interplanetary dust particles (IDP; 4 × 10⁻¹⁰ tons yr⁻¹ (Pavlov et al., 2005b)), as a function of sedimentation speed, the thick red solid line defines an enhanced IDP: corresponds to the dark cloud encounter with density is 10³ protons/cm³, and relative velocity of solar system and cloud is 10 km s⁻¹, while the horizontal dash line defines the iridium detection limit through radiochemical neutron activation analysis (0.02–0.05 ppb) (Kyte et al., 1995). The iridium anomaly is detectable, only where the sedimentation speed is lower than ~3 m Myr⁻¹ (vertical dash line). We found that the four periods of the Site 886C (I, II, III, and VI) are above the detection limit (horizontal dash line). On the other hand, the average sedimentation speeds of Site 463 (Thiede et al., 1981), 525 A (Shackleton et al., 1990), and 690C (Stott and Kennett, 1990) in End-Cretaceous turns out of less than the detection limit, therefore the detection of encounter components is difficult there, because of the dilution by the Earth’s materials to be detected.](image)

![Fig. 2. Location of Sites 463, 525 A, 690C, and 886C. Configuration of continents and site locations at 65 Ma (red) and at present-day (blue), with solid lines delineating travel paths (Thiede et al., 1981; Snoeckx et al., 1995; Li and Keller, 1999). An iridium anomaly is caused by extraterrestrial material and concentration of iridium-rich material of Earth (e.g., manganese nodule). These extraterrestrial and terrestrial factors can be distinguished by multi-component analysis through a Co–Ir diagram as discussed below.](image)

2. Co–Ir diagram

The iridium abundance is plotted against cobalt abundance in Fig. 3, normalized by those of CI chondrite. The large open squares represent Earth’s surface materials (Table 1) (i.e., marine organisms (Martic et al., 1980; Wells et al., 1988), earth crust (Taylor and McLennan, 1985), pelagic clays (Goldberg et al., 1986; Terashima et al., 2002), and manganese nodule (Harriss et al., 1968; Glasby et al., 1978; Usui and Moritani, 1992)). The large solid squares represent CI chondrite (Lodders, 2003). The cobalt abundance of pelagic clays is used 222 ± 41 ppm (Terashima et al., 2002) as similar to 886C sample which are slow sedimentation rate (<1 m/Myr) and deep (>5000 mbsf) sea sediment. The positive and negative error value for iridium and cobalt abundance for crust are adopted upper and lower crust (Taylor and McLennan, 1985). Any mixtures of the Earth’s surface materials must distribute in the gray area taken into account the measurement errors (3σ in iridium abundance. The standard deviation of the iridium is estimated by the data in 0.75–54.4 mbsf of the core,) and statistical error. The statistical error is estimated by Table 1. These values of the uncertainty are consistent with the detection limited reported in Kyte et al. (1995). We found that most of the data points in 886C are located well above the curves.

Here, the iridium abundance of a mixture of Earth’s surface material is calculated through three linear combinations of materials of Earth, including marine organisms (MO), marine crust (MC), pelagic clays (PC), and manganese nodule (MN), with the contribution of exosolar material (Y_ex) as

\[ Y_{EX} = Y - \left( \frac{3.0 \times 10^{-6}}{C_1} X + \left( \frac{1.4 \times 10^{-5}}{C_2} \right) \right) \] for MO to MC,
\[ Y_{EX} = Y - \left( \frac{2.1 \times 10^{-6}}{C_1} X + \left( \frac{4.0 \times 10^{-5}}{C_2} \right) \right) \] for MC to PC,
\[ Y_{EX} = Y - \left( \frac{2.6 \times 10^{-6}}{C_1} X - \left( \frac{7.3 \times 10^{-5}}{C_2} \right) \right) \] for PC to MN,

where Y and X are iridium and cobalt abundances in ppm. Assuming that the excess iridium abundance in the sediment originates from exosolar materials, the extraterrestrial index f_EX can be defined as

\[ f_{EX} = Y \left( \frac{Y_{EX}}{Y_{CI}} \right) \]
It is worth noting that this iridium-enriched zone continues over 5 m, which corresponds to the ages from Campanian to Danian. Neither diffusion nor bioturbation can explain this broad anomaly because of the following reasons: (1) the redistribution of platinum-group element such as Pt, Re, and Ir is generally less than 10 cm (Colodner et al., 1992); (2) the mean depth of marine bioturbation is as small as ~10 cm (Boudreau, 1998), which is much less than the width of the broad component (~5 m), and (3) the evidence of bioturbation is minor in the core.

Period II (small solid squares in Fig. 3 and Table 2, 62.85–64.10 mbsf) covers from Danian age (61.6–66.0 Ma) to Ruperian age (28.1–33.9 Ma). The sedimentation rate is 0.04 m Myr\(^{-1}\), which is the second slowest among the four periods. The features in this period plot significantly above the gray area. This excess in iridium can be explained by the present IDP flux. In other words, no extra IDP flux is necessary.

The sedimentation rate of Period III (open circles in Fig. 3 and Table 2, 58.60–62.85 mbsf) is estimated to be 0.4 m Myr\(^{-1}\), covering Ruperian age (28.1–33.9 Ma) and Aquitanian age (20.44–23.03 Ma). In the Co–Ir diagram (Fig. 3), the open circles are plotted in the gray area. The iridium abundance of this period can be explained by the mixtures of the materials on the surface of the Earth.

The period IV (small open squares in Fig. 3 and Table 2, 58.35–58.06 mbsf) covers Aquitanian age (20.44–23.03 Ma) and Tortonian age (7.246–11.63 Ma). The sedimentation rate is 0.02 m Myr\(^{-1}\), which is the slowest among the four periods.

In summary, Period I requires an enhanced flux of extraterrestrial materials probably caused by an encounter with a dark cloud to explain the relatively high iridium abundance, while other periods can be explained by a mixture of surface materials of Earth, if the present level of IDP is taken into account. Officer and Drake (1985) argued that the iridium anomaly can be explained by a mixture of volcanic basalt like Kilauea. However, the Co–Ir diagram (Fig. 3) shows that the data points of the broad component of Period I (open circles) are distributed in a region different from those of the Decan Trap (solid triangle of Fig. 3) and Hawaii (open triangle of Fig. 3). The volcanic basalts, which locate in the gray area cannot produce materials outside the area.

### 4. Dark cloud encounter

Fig. 5a shows the estimated flux of exosolar material of 10–80 Ma through (1) and (2). We assumed a density of the core sample to be 3 g cm\(^{-3}\). The enhanced flux of exosolar material began ~73 Ma and has continued to fall through ~8 Myr. The peak at 66 Ma is likely to be originated from an asteroid impact which formed the Chicxulub impact crater (Kyte et al., 1995). On the other hand, the broad component can be explained not solely by the Chicxulub impact but by an encounter with a giant molecular cloud. The encounter leads to a “Nebula Winter” (Kataoka et al., 2013, 2014), in which an environmental catastrophe of the Earth is driven by an enhanced flux of cosmic dust particles and cosmic rays, which cause global cooling and destruction of the ozone layer (Fig. 6).

The scale on the right hand side of Fig. 5a denotes the density of nebula N, corresponding to dust flux in the case of relative velocity of the solar system and cloud V is 10 km s\(^{-1}\) and 20 km s\(^{-1}\) by following equation:

\[
N = 1000 \text{ protons/cm}^3 \left( \frac{f_{\text{ex}}}{1.0 \times 10^{-8} \text{kg m}^{-2} \text{yr}^{-1}} \right) \left( \frac{V}{20 \text{ km s}^{-1}} \right) + 4.6 \left( \frac{V}{20 \text{ km s}^{-1}} \right)^{-2}.
\]

The dark cloud density of 2000–6000 protons/cm\(^3\) corresponds to the climate forcing (F) of snowball earth (~9.3 W m\(^{-2}\) (Pavlov et al., 2005b)), depending on the relative velocity (Fig. 5), for the case that

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### Table 1

Iridium and Cobalt abundances of marine organisms (Martic et al., 1980; Wells et al., 1988), earth crust (Taylor and Mclennan, 1985), pelagic clays (Goldberg et al., 1986; Terasinha et al., 2002), and manganese nodule (Harriss et al., 1968; Glasby et al., 1978; Usui and Moritani, 1992) and CI chondrite (Lodders, 2003) plotted in Fig. 3.

|                  | Ir (ppb) | Co (ppm) |
|------------------|----------|----------|
| Marine organism  | 0.02 ± 0.02 | 2 ± 2    |
| Crust            | 0.1 (0.02–0.13) | 29 (10–35) |
| Pelagic clay     | 0.5 ± 0.3   | 232 ± 41  |
| Manganese nodule | 8.18 ± 7.50 | 3200 ± 1300 |
| CI chondrite     | 470 ± 5    | 502 ± 17  |
typical size ($a$) and density ($\rho$) of cosmic dust particles are 0.2 $\mu$m and 3 g cm$^{-3}$ by following equation (Kataoka et al., 2013):

$$ f_{EX} = \left( 3.1 \times 10^{-7} \frac{kg}{m^2 \cdot yr^{-1}} \right) \left( \frac{F}{20 W m^{-2}} \right) \left( \frac{a}{0.1 \mu m} \right)^{23} \left( \frac{\rho}{10^3 kg m^{-3}} \right) $$

(4)

The nebula density, which is the density about 10$^3$ protons/cm$^3$, can be seen in a typical dark nebula core. It is worth noting that the optical depth is given as (Kataoka et al., 2013).

$$ \tau = 1.1 \times 10^{-2} \left( 3.1 \times 10^{-7} \frac{kg}{m^2 \cdot yr^{-1}} \right) \left( \frac{f_{EX}}{10^2 \frac{W}{m^2}} \right) \left( \frac{a}{0.2 \mu m} \right)^{-1} \left( \frac{\rho}{10^3 kg m^{-3}} \right)^{-1} $$

(5)

where $t$ is the residence time in the stratosphere estimated as (Kataoka et al., 2013).

$$ t = 18 \text{yr} \left( \frac{a}{0.2 \mu m} \right)^{-1.3} $$

(6)

The optical depth is as high as $-0.045$ (Fig. 5a).

Fig. 6 depicts the concept of the encounter with the dark cloud. During the encounter of a dark cloud, the fluxes of cosmic dust particles and cosmic rays are enhanced. Both of them lead to global climate cooling. The following three evidences show that global cooling took place well before K-Pg boundary (~73–65 Ma).

First, the oxygen isotope ratio shows strong climate cooling. The lighter oxygen $^{16}$O tends to be contained more in water vapor than in heavier $^{18}$O. This lighter water vapor will settle down to the land as snow to form massive ice sheets on the continents. Therefore, the lower $\delta^{18}$O is incorporated in the ice sheets on the continents, while the higher $\delta^{18}$O remains in the ocean. The shell of planktonic and benthic foraminifera is a good indicator of oceanic $\delta^{18}$O. Their dead bodies settle along the ocean floor to form a sediment layer. Therefore, the positive anomaly in oxygen isotope ratio (Fig. 7) (Barrera and Huber, 1990; Ingram, 1995; Sugarman et al., 1995) can be considered as a result of the extension of the continental ice sheet, which suggests global cooling during the End-Cretaceous from ~73 Ma. The trends of $\delta^{18}$O can also be consistently seen in low-, mid-, and high-latitude ODP samples (Site 463, 525 A, and 690C).

Second, global cooling is also suggested by high $^{87}$Sr/$^{86}$Sr ratios. The development of an ice sheet leads to both marine regression and exposure of continental shelves. The resultant enhancement of denudation and weathering leads to a high $^{87}$Sr/$^{86}$Sr because of a high $^{87}$Sr/$^{86}$Sr in the continental crust. The increase in $^{87}$Sr/$^{86}$Sr during the End-Cretaceous (Fig. 8) (Barrera and Huber, 1990; Ingram, 1995; Sugarman et al., 1995) suggests an increase in denudation and weathering beginning at ~73 Ma and continuing for ~8 Myr due to the lower sea level, which indicates a globally cool climate. The trends of $^{87}$Sr/$^{86}$Sr can also be consistently seen in low-, mid-, and high-latitude ODP samples.

Table 2
Summary of the analysis of the core sample of 886C and volcanic materials of Decan Trap and Hawaii.

| Symbol | Period | Depth (mfd) | Age (Ma) | Sedimentation speed (m/Myr) | Putative origin of iridium | Extraterrestrial flux ($\times$present IDP) |
|--------|--------|-------------|----------|---------------------------|---------------------------|----------------------------------------|
|        | min    | max         | min      | max                       | Terrestrial               | 0.31                                   |
| □      | 58.35  | 58.60       | 11.61    | 22.27                     | -0.2                      | Terrestrial                           |
| □      | 58.60  | 62.85       | 22.27    | 33.64                     | -0.4                      | Terrestrial                           |
| □      | 62.85  | 64.50       | 33.64    | 63.87                     | -0.04                     | Terrestrial                           |
| □      | 64.10  | 65.03       | 63.87    | 65.59                     | Usual IDP                 | 1.4 ± 0.7                             |
| □      | 65.03  | 65.50       | 65.59    | 66.46                     | Extraterrestrial          | 33 ± 10                               |
| □      | 65.50  | 71.60       | 66.46    | 77.77                     | -                         | 8.3 ± 0.7                             |
| □      | 71.60  | 72.20       | 77.77    | -                         | -                         | 8.3 ± 0.7                             |

Deccan trap

Volcanic material of Hawaii

Fig. 4. Geological age (a), iridium abundance (b) (Kyte et al., 1995), cobalt abundance (c) (Kyte et al., 1995), extraterrestrial index (d), and sedimentation rate (e) (Snoeckx et al., 1995), as well as the pelagic deep sea sediments sampled at 886C, marking the End-Cretaceous around the K-Pg boundary. The blue area cannot be explained by any mixture of the surface materials of the Earth.
Finally, the sea-level changes in End-Cretaceous (Hallam and Wignall, 1999) can be caused by an extension of the continental ice sheet.

The long period of climate cooling forced by a dark-cloud encounter may account for a mass extinction at the end of the Cretaceous. It is also consistent with a trend of the reduction in generic number of dinosaur (Sloan et al., 1986) (Fig. 5b), as well as ammonite (Hancock, 1967; Wiedmann, 1973; House, 1989, 1993).

5. Chicxulub impact at K–Pg boundary

The mass extinction at the K–Pg boundary is widely thought to have been caused by an impact of an asteroid (e.g., Alvarez et al., 1980; Schulte et al., 2010) at 65.5 Ma. However, a complete extinction of the total family by just one asteroid impact seems rather difficult because of the following two reasons. First, a severe perturbation in the global environment of Earth would finish nearly 5 years after the impact (Planetary Science Institute, 2015), the solid particles (including sulphate) launched by the asteroid impact would settle down in only a few months (troposphere) to a few years (stratosphere), and a negative radiative forcing would become negligible a few years subsequent to the impact. For example, the effect of the sunshield by launched solid particles and sulphate into the atmosphere of the Earth from the eruptions of the Pinatubo (June 1991, 20 Mt) and Toba (about 71 kyr ago, 1 Gt) volcanoes completely vanished after 3–5 years (Planetary Science Institute, 2015). Even if 100 times larger than the Toba eruption, as is the estimated case of the Chicxulub impact, the sunshield effect would not persist beyond about 5 years, because the retention time is determined by convection time of stratosphere. Individuals of those few percentage of surviving species would recover completely after the environmental catastrophe was over.

Second, there have been impact events of similar scale to that of Chicxulub without catastrophe of the global environment/biosphere, such as the Woodleigh, Chesapeake Bay, and Popigai impact cratering.
events. In particular, there is no discernable evidence for a Late Devonian (364 Ma) mass extinction related to the formation of the 120-km-diameter Woodleigh crater in western Australia (Mory et al., 2000a, 2000b; Uysal et al., 2001; Glikson et al., 2005), about ~80% the size of the Chicxulub crater (~150 km diameter) (Earth Impact Database, 2015). The 85-km-diameter Chesapeake Bay (Poag et al., 2002) and the 100-km-diameter Popigai (Earth Impact Database, 2015) impact craters were formed during Late Eocene epoch in America and Russia, respectively. Also respectively, the diameters of these craters are ~57% and ~67% of Chicxulub crater. Furthermore, in the case of the Popigai crater, the stratospheric injection of impact-produced sulfur (~2 × 10^{15}–4 × 10^{16} g) is similar to that determined for the Chicxulub crater (10^{14}–10^{16} g) (Kring et al., 1996), though no mass extinction took place. Therefore, why only the Chicxulub impact would lead to mass extinction but not the other three comparable impacts is difficult to explain by an impact hypothesis alone.

It is worth noting that an encounter with the dark cloud perturbs the orbit of asteroids and comets through its gravitational potential, causing showers of asteroids and/or comets, and likely associated impact events (Kataoka et al., 2014). The asteroid impact at K–Pg, therefore, may be one of the consequences of the dark cloud encounter. On the other hand, the broad component that span more than 8 Myrs is unlikely to be caused by a collision in the asteroid belt, since the fall down time scale of 0.2 μm dust from the asteroid belt (~3 AU) is as short as ~6000 yrs. because of Poynting Robertson effect (Burns et al., 1979).

We conclude that the cause of the cold climate at the End-Cretaceous was driven by an encounter with a giant molecular cloud, with such an encounter and related perturbation in global climate a more plausible explanation for the mass extinction than a single impact event, Chicxulub.

6. Conclusion

We found that the multi-component analysis and “extraterrestrial index” f_{ex} are effective to show the evidence of the abnormal extraterrestrial flux in the past Earth from deep-sea sediments. This method can be applied (and further tested) to other periods of drastic change in the Earth’s environment such as End-Triassic, End-Permian, F–F boundary, and End-Ordovician events, recorded in the sedimentary records of accretionary prisms. The oxygen and strontium isotope ratios are consistent with the gradual cooling of the End-Cretaceous period due to the encounter with a giant molecular cloud. It is also consistent with the gradual decrease of the number of genera. If this hypothesis is correct, then other index elemental information (e.g., platinum group elements and stable isotope ratios) and the distribution of spherules of exosolar origin will coeval with the broad component of the iridium anomaly (Ib). The spherules will be found as investigation proceeds of deep sea sediments. A glacial deposit such as tillite and/or dropstone are expected to be found.

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Fig. 7. Oxygen isotope ratio based on low-, mid-, and high-latitude ODP samples (Site 463, 525 A, and 690C) (Barrera and Huber, 1990; Li and Keller, 1998; Barrera and Savin, 1999; Li and Keller, 1999) for the latest Cretaceous. The dashed and solid lines represent planktonic and benthic foraminifera, respectively. A model temperature was calculated using \( T = 16.28 - 4.47(\delta_{c} + 1) + 0.109(\delta_{c} + 1) \) (Barrera and Savin, 1999), where \( \delta_{c} \) is the \( \delta^{18}O \) value of the foraminifer CaCO3 relative to Pee Dee Belemnite. However, the temperatures, which are calculated using the \( \delta^{18}O \) value of benthic foraminiferal species, are about one degree lower than this model temperature.

Fig. 8. Strontium isotope ratio (87Sr/86Sr) based on low-, mid-, and high-latitude ODP samples (463, 525 A, 690C, and 886C) (Barrera and Huber, 1990; Ingram, 1995; Sugarman et al., 1995) for the latest Cretaceous.
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