# DISCUSSION AND REPLY

## From Cosmic Explosions to Terrestrial Fires? A Discussion

*Frédéric Deschamps*[1,*] *and Fabrice Mottez*[2]

*1. Institute of Earth Sciences, Academia Sinica, 128 Academia Road, 11565 Taipei, Taiwan; 2. Laboratoire Univers et Théories, Centre National de la Recherche Scientifique, Observatoire de Paris–Université Paris Sciences et Lettres, Université de Paris, 5 Place Jules Janssen, 92190 Meudon, France*

Several observational studies have revealed the explosion of a supernova in the early Pleistocene at about 100 pc from the Solar System. The proof of this explosion is based on the signature associated with $Fe^{60}$ deposits in Earth's sediments and on the Moon's regolith. The supernova remnant was the cause of additional input of galactic cosmic rays (GCRs) in the Solar System. Their propagation from the supernova remnant to Earth and the effects of the associated cascades of secondary particles triggered by their interaction with Earth's atmosphere were analyzed by Melott and Thomas (2019). According to their study and previous works cited in their article, high-energy cosmic rays (above 1 TeV) caused a 20-fold increase of irradiation by muons on Earth's surface and on the ocean and an order of magnitude increase of the atmospheric ionization that could have lasted more than 1,000 years. The increase in irradiation could have contributed to a minor mass extinction in the Pliocene–Pleistocene transition, 2.6 My ago. Melott and Thomas (2019) analyzed the climatic consequences of the increased atmospheric ionization leading to more frequent lightning and, therefore, to an increase in nitrate deposition and in wildfires. Increased wildfires, evidenced by an increase in soot and carbon deposits over the relevant period, would have contributed to the transition from forest to savanna in northeastern Africa, long argued to have been a factor in the evolution of hominin bipedalism.

In this discussion, we argue that the Gauss-Matuyama Earth's magnetic field reversal, which defines the Pliocene–Pleistocene transition (Suc et al. 1997), could have enhanced the impact of the GCRs related to the early Pleistocene supernova discussed by Melott and Thomas (2019).

Although they discussed various hypotheses concerning the interstellar magnetic field, they voluntarily neglected the variations of local magnetic fields on the impact of cosmic rays. They base their choice on a work by Jackman et al. (2016) in which the effect of GCRs on atmospheric chemistry is analyzed during the 1960–2010 epoch. More specifically, Jackman et al. (2016) showed that local magnetic field fluctuations of a factor of two at Earth's poles over a solar cycle only have a moderate effect. These conclusions are correct only if Earth's magnetic field has a dominant dipole component, as is the case in the present epoch analyzed in Jackman et al. (2016) and during most of Earth's history. By contrast, they certainly do not apply to geomagnetic excursions and magnetic field polarity reversals, which have episodically affected Earth's magnetic field. Paleomagnetic studies show that these events are usually short (a few thousand years) compared with the geological timescale and have occurred many times in the past but not periodically. Most importantly for our discussion, during these events, the shielding provided by the magnetic field is lost, thus potentially increasing the impact of GCRs on the biosphere.

Magnetic field reversals and geomagnetic excursions are complex events during which the dipolar component of the magnetic field is unstable and weak (e.g., Glatzmaier and Coe 2015). In most if not all reversals, the intensity of the

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* Author for correspondence; email: frederic@earth.sinica.edu.tw.

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dipole is strongly reduced. In addition, some reversals show complex directional changes; that is, the locations of the (virtual) geomagnetic poles change rapidly, and the polarity may swing several times before settling to normal or reverse. The whole process may last several thousand years and in some cases up to 20,000 years.

The reduction in magnetic field intensity and the rapid changes in the direction of the dipole have important consequences on the propagation of charged particles. Low-energy cosmic rays are partly guided by magnetic field lines and, with the present dipole magnetic field that is implicitly supposed in Melott and Thomas (2019), the ratio of ionospheric ionization at the poles and at the equator is almost one order of magnitude (Jackman et al. 2016, fig. 1). When the dipole field was reduced or canceled or when the virtual poles were located at low or intermediate latitudes, the intertropical zone, where African savanna is situated, could have been exposed to the direct influx of cosmic rays as the poles are today.

The Gauss-Matuyama magnetic field reversal is used to define the boundary between the Pliocene and Pleistocene epochs (Suc et al. 1997) and has been dated to 2.589 ± 0.003 Ma based on lacustrine sediments (Deino et al. 2006). This age is compatible with the age of the supernova and associated $\mathrm{Fe}^{60}$ deposits as discussed previously. Although the Gauss-Matuyama reversal has been dated precisely, paleomagnetic studies indicate that the magnetic field has been unstable for more than 10 ky around this date. For instance, Glen et al. (1999) reported fluctuations of the magnetic field direction indicating a total transition time of about 15 ky. Yang et al. (2014) made similar observations from samples collected in a different region and concluded that the transition lasted more than 11 ky. Also worthy of interest, Goguitchaichvili et al. (1999) estimated that, during the Gauss-Matuyama transition, the intensity of the magnetic field in southwestern Iceland was on average 14.8 ± 4.6 $\mu$T (compared with 52.1 $\mu$T today), corresponding to a decrease of the magnetic dipole moment by a factor of two. Therefore, during the Gauss-Matuyama transition, the biosphere may have been unprotected from cosmic rays for 10–15 ky.

The increased input of GCRs associated with a supernova may also last for a few thousand years (Brahimi et al. 2020). The impacts of the arrival of supernova GCRs and the magnetic field reversal can be combined if the two phenomena occurred at the same time, as might have been the case 2.6 My ago. The possible effect of the partial or total cancellation of Earth's magnetic dipole component during the Gauss-Matuyama magnetic reversal could thus be included in further work following the study by Melott and Thomas (2019). This effect would most probably reinforce their conclusion regarding the impact of the supernova occurring 2.6 My ago as a possible cause of the Pliocene–Pleistocene transition.

*Addendum*. We acknowledge authors A. L. Melott and B. C. Thomas for their answer, and we agree with their argument that the highly energetic particles studied in their article are not influenced by the geomagnetic field deflection. We still consider that the increase of the lower-energy GCRs (abundant, e.g., in cases A and C in Thomas et al. [2016]), which are influenced by Earth's magnetic field, may have enhanced the cloud cover. Empirical studies show the influence of the lower-energy GCRs (those below 20 GeV measured with neutron monitors) on the cloud cover (Svensmark 1998; Harrison and Stephenson 2006). This finding is complementary to the process described in Melott and Thomas's article with higher-energy cosmic rays, and it reinforces the conclusions regarding the influence of a nearby supernova as a trigger of a cooling of the climate and wildfires. As for other geological events, the Pliocene–Pleistocene transition may result from an addition of independent causes with similar consequences.

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