The Meteoritical Society

Meteoritics & Planetary Science 44, Nr 8, 1115–1120 (2009)
Abstract available online at http://meteoritics.org

Formation age of the lunar crater Giordano Bruno

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(Received 18 January 2009; revision accepted 24 May 2009)

Abstract–Using the Terrain Camera onboard the Japanese lunar explorer, SELENE (Kaguya), we obtained new high-resolution images of the 22-kilometer-diameter lunar crater Giordano Bruno. Based on crater size-frequency measurements of small craters (<200 m in diameter) superposed on its continuous ejecta, the formation age of Giordano Bruno is estimated to be 1 to 10 Ma. This is constructive evidence against the crater's medieval age formation hypothesis.

INTRODUCTION

Giordano Bruno is a 22-kilometer-diameter crater located just beyond the northeastern limb of the Moon (36°N, 103°E). This crater has an extensive ray system rivaling that of Tycho crater (Whitaker 1963), yet its diameter is only about one-fourth that of Tycho (Fig. 1). Based on a survey of large, bright-rayed craters on the Moon, Hartung (1976) reported that Giordano Bruno has a higher ray-length-to-crater-diameter ratio than any crater on the Moon.

Although there are some craters with rays resulting from compositional contrast with the surrounding terrain, not because of the presence of immature material (e.g., Hawke et al. 2004), it is apparent from spectral studies that Giordano Bruno ejecta are extremely immature (Pieters et al. 1994; Grier et al. 2001). Clementine UV-VIS images indicate that the Giordano Bruno rays are the most immature among 64 large craters (≥20 km in diameter) previously mapped as possessing rays (Grier et al. 2001). These observations suggest that Giordano Bruno is the youngest lunar crater of its size or larger.

Medieval chronicles of Gervase of Canterbury reported "upper horn of a new moon split and from the division point fire, hot coals, and sparks spewed out" (Newton 1972). Hartung (1976) interpreted this as an eyewitness account of the impact on the Moon that formed Giordano Bruno, and thus suggested that the crater was formed on June 18, 1178.

This hypothesis has often been associated with other historic June events, such as the Tunguska explosion in 1908 and the meteoroid storm that was seismically observed on the Moon in 1975 (Hartung 1993); a celestial body forming Giordano Bruno in AD 1178 might have arrived from the same radiant as these objects, thus a common source might be shared by the bodies causing these events. Also, Calame and Mulholland (1978) argued that large amplitudes of the free librations of the Moon might be explained by a recent large impact, e.g., the one that formed Giordano Bruno. Furthermore, if the hypothesis of the Giordano Bruno formation in medieval times is correct, the substantially high degree of space weathering found along the wall of Giordano Bruno may indicate that the weathering process on the Moon is far more rapid than currently expected (Pieters et al. 1994).

However, the hypothesis of the formation of Giordano Bruno in medieval times is not unanimously accepted. For example, there is no historical record of a large meteor storm that should have occurred in the Earth's atmosphere after Giordano Bruno formation (Withers 2001). Also, Nininger and Huss (1977) suggested a meteor transiting the Moon as one possible astronomical explanation of the eye-witnessed transient phenomenon.

To critically test the medieval formation hypothesis, we determined the absolute formation age of Giordano Bruno by crater counting. We obtained high-resolution images around the Giordano Bruno crater from the Terrain Camera onboard the lunar explorer SELENE (Kaguya) (Kato et al. 2008). Crater counting is a well-established technique to derive

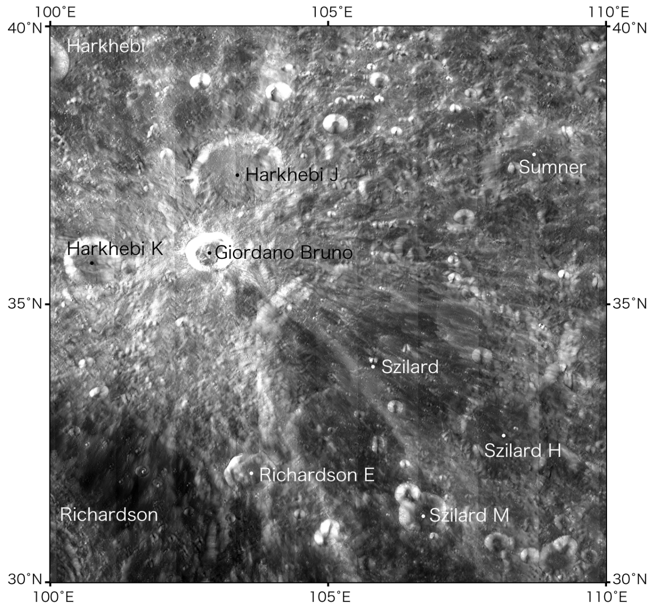

Fig. 1. TC mosaic image showing Giordano Bruno crater and its ray system; simple cylindrical map projection.

relative and absolute ages of planetary surfaces (e.g., Hartmann 1970, 1972; Neukum et al. 1975; Neukum 1983; Neukum and Ivanov 1994; Hiesinger et al. 2000; 2003; Hartmann and Neukum 2001; Neukum et al. 2001; Stöffler and Ryder 2001). Based on the simple idea that older surfaces accumulate more craters, we can infer the relative age by measuring the crater size-frequency distribution (CSFD) with remote sensing image data. The cratering chronology formulated by relating crater frequencies to the radiometric ages of Apollo and Luna samples enables us to convert the crater frequency into an absolute model age.

We will also present results of age determinations of three other craters, Byrgius A (19.7 km), Moore F (24.2 km), and Necho (31.2 km) for comparison. These craters also have intensive, bright ray systems and were previously classified into the youngest group defined as younger than Tycho crater (109 Ma) as well as Giordano Bruno. Grier et al. (2001) investigated spectral maturities of ejecta of 64 rayed craters using Clementine multispectral images and indicated that Giordano Bruno and the three craters have more immature ejecta than Tycho crater.

TC DATA OF THE GIORDANO BRUNO AREA

The Terrain Camera (TC) onboard SELENE is currently acquiring images of the entire surface of the Moon at a spatial resolution of 10 m/pixel (Haruyama et al. 2008), more than 10 times higher resolution than previous image data around Giordano Bruno. The TC data enable us to perform crater counts of craters even much less than 100 m in diameter, which is sufficiently small for our purpose.

TC images of the Giordano Bruno area were acquired in February 2008, with a low Sun elevation angle (35° from the horizontal plane). Extremely fresh features of Giordano Bruno are found in the images (Fig. 2), including a pristine rim, smooth internal melt ponds, a large number of boulders inside and outside the crater, and a pristine ejecta blanket around the crater.

Unexpectedly, however, numerous small craters (≤200 m in diameter) were found in the interior and on the continuous ejecta of Giordano Bruno. Because the continuous ejecta surrounding Giordano Bruno forms one of the youngest surface units on the Moon, there should be no contamination by secondary craters from other recently formed large craters. Therefore, we consider the small craters as primary craters that were formed after the formation of Giordano Bruno.

The large number of boulders and landslides from the inner wall of the rim inhibit identification of small craters in the interior of Giordano Bruno. Therefore, we focused on counting small craters on the continuous ejecta, rather than those inside Giordano Bruno.

We used images that are map-projected in a transverse Mercator projection with a resolution of 10 m/pixel for crater counts because the projection introduces little distortion in a narrow area. The scale at an angular distance of 1° from the central meridian of projection is less than 0.02% greater than the scale at the central meridian. The central meridian was set at 103°E longitude at the center of Giordano Bruno.

CRATER SIZE-FREQUENCY MEASUREMENTS

The technique of crater size-frequency measurement has been described in detail by numbers of papers (e.g., Neukum and Ivanov 1994; Hiesinger et al. 2000, 2003; Hartmann and Neukum 2001; Neukum et al. 2001; Stöffler and Ryder 2001). Therefore, we will just briefly present the procedure.

We counted the craters within the area of the continuous ejecta out to one crater radius from the rim (Fig. 2), whose total area is 294 km^2. Crater counts were performed manually on the computer. The diameters of small craters were calculated by multiplying a crater diameter in a unit of image pixel and the pixel resolution (10 m/pixel).

Crater size-frequency measurement is sensitive to any contamination by secondary craters (e.g., Namiki and Honda 2003; McEwen and Bierhaus 2006). As described above, however, we consider the small craters superposed on the continuous ejecta of Giordano Bruno as primary craters, and thus we can use them to determine the absolute model age of Giordano Bruno.

We used the lunar standard CSFD and the cratering chronology model proposed by Neukum and co-workers (Neukum 1983; Neukum and Ivanov 1994) to obtain the absolute model age from the CSFD measurement. More recently, the standard CSFD and the chronology model were updated (Neukum et al. 2001; Stöffler and Ryder 2001). However, in the diameter range (a few hundred meters to a

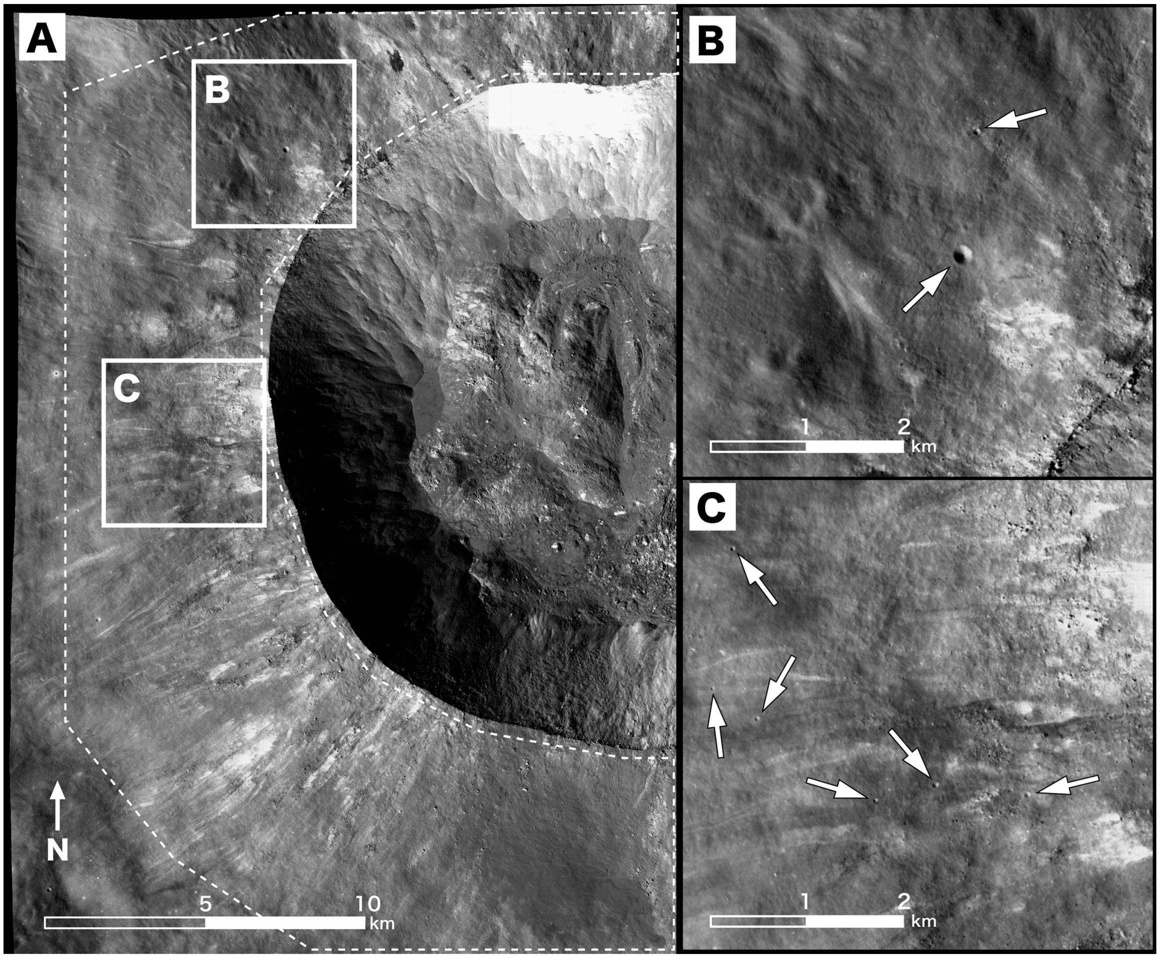

Fig. 2. A) TC high-resolution image of the area surrounding Giordano Bruno crater. The spatial resolution of this image is 10 m/pixel. Crater size-frequency distribution measurements were performed for the area indicated by the dashed line. This is an orthographic image produced by high-resolution images and the TC-derived Digital Terrain Model. B) Close-up image immediately north-west of the rim. Arrows indicate craters larger than 40 m in diameter. C) Close-up images of the continuous ejecta showing a few small craters larger than 40 m in diameter (arrows). The images are presented in a transverse Mercator map projection.

few tens of meters) and the age range (≤0.1 Ga) used in this study, the differences between the models are insignificant (Neukum et al. 2001) and hardly produce difference in the estimated ages.

The model ages from crater counts are principally limited by the statistical error (Neukum et al. 2001). The statistical error of individual data points in our crater frequency measurements is mostly <30% (1σ); the errors of ages based on the chronology model are of ±0.02 Ga for >3.5 Ga, 0.01–0.03 Ga for between 3.2–3.0 Ga and <30% for <3.0 Ga (Hiesinger et al. 2000).

FORMATION AGE OF GIORDANO BRUNO

We counted 49 craters larger than 40 m in diameter, which are shown in Fig. 3 as a cumulative size-frequency distribution plot of the craters. If the recent formation hypothesis is correct, the size distribution should plot on an isochron of 1 ka. However, the observed distribution lies between 1 to 10 Ma. The least-squares fit of the standard size distribution (Neukum 1983; Neukum and Ivanov 1994) to the plots in a diameter range of 40 to 80 m gives a crater density of 3.2×10^{-6} km^{-2} at a diameter of 1 km, corresponding to a model age of 4 Ma (Fig. 3).

We performed a numerical Monte Carlo simulation to evaluate the error in age determination due to statistic fluctuation of the crater production frequency. For a test unit of a given area and age, craters were randomly sampled until the number of sampled craters equals the ideal number of craters calculated for that area and age from the Neukum's cratering chronology model. A simple power law $N \propto D^{-b}$ was then used as a probability distribution for the random sampling, where D is crater diameter. The size-frequency distribution of the sampled craters was measured and converted to the absolute model age. Iterating this procedure, we evaluated the error in age determination due to statistic fluctuation. Details of model assumptions and parameters in the simulation were given by Morota et al. (2008). The result

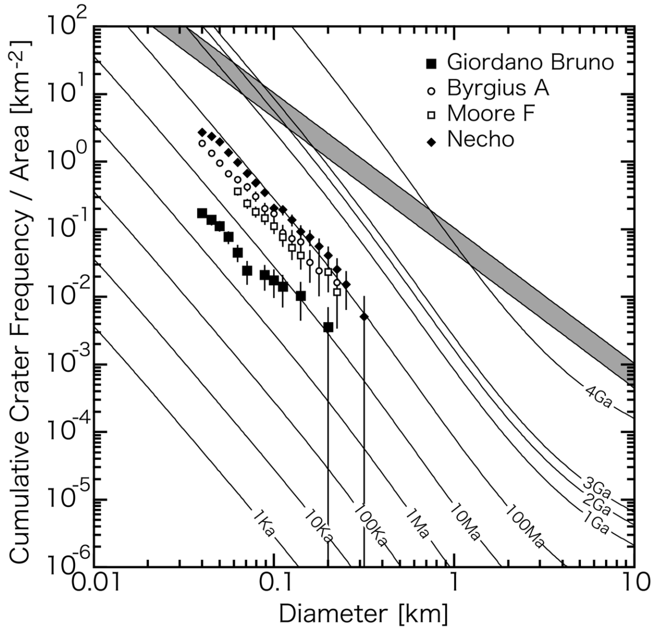

Fig. 3. Cumulative size-frequency distribution of craters counted on the continuous ejecta of Giordano Bruno. Error bars are calculated by $(N \pm N^{1/2})/A$, where N is the cumulative number of craters and A is the counted area. The isochrons are calculated from Neukum's lunar standard size-frequency distribution and cratering chronology curve (Neukum 1983; Neukum and Ivanov 1994). The grey zone indicates a saturation equilibrium level (e.g., Gault 1970), corresponding to 3 to 7% of the geometric saturation. Crater frequencies on continuous ejecta of other craters classified into the youngest group (Grier et al. 2001) are also shown for comparison.

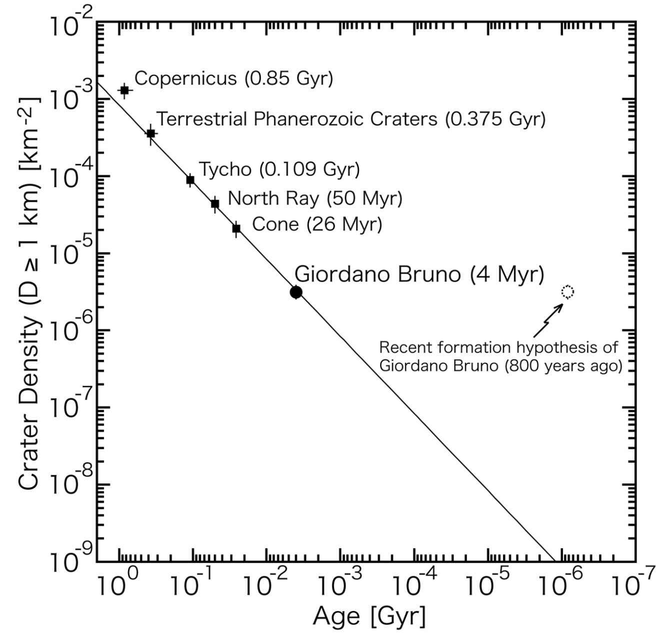

Fig. 4. Lunar cratering chronology for the last 1.0 Gyr (Neukum 1983; Neukum and Ivanov 1994). Solid squares plot observed relations between absolute ages of Copernicus, Tycho, North Ray, and Cone craters and small-crater frequencies measured on their ejecta blankets (Neukum 1983; Neukum and Ivanov 1994), as well as the terrestrial Phanerozoic cratering record (Grieve and Dence 1979) recalculated to lunar impact conditions. The circles show the position of Giordano Bruno in this diagram for the measured crater density on its ejecta blanket and assuming the linear relationship between ages and cratering frequencies by Neukum and Ivanov (solid circle) as well as the young age hypothesis (open circle). Crater density for craters >1 km in diameter is extrapolated from the measurements (Fig. 3).

gives the error (1σ) of about 0.8 Ma due to statistic fluctuation for an area of 294 km^2 and an age of 4 Ma. Therefore, it is extremely unlikely for a unit with an age of 1 ka to exhibit a crater density as old as 4 Ma.

The existence of small craters on Giordano Bruno could not be the result of a recent increase in crater production rate for three reasons. First, the rate required to yield an age of 800 yr becomes too large. For craters larger than 1 km in diameter, the rate would be 4.0×10^{-9} km^{-2} yr^{-1} (= 3.2×10^{-6} km^{-2}/800 yr), which is about 4,800 times higher than the constant rate (8.4×10^{-13} km^{-2} yr^{-1}) (Fig. 4). Second, there is no report of such an extremely high production rate on Earth. Third, previous studies of terrestrial and lunar cratering records have argued for a constant rate (within a factor of 2) (e.g., Neukum et al. 2001; Hartmann et al. 2007). For example, the relations between absolute ages of young lunar craters and small crater frequencies measured on their ejecta blankets indicate a constant flux rate for the last 100 Myr (Fig. 4). Furthermore, a comparison of the satellite records of bolide detonations in the Earth's atmosphere with the cratering records on the Moon indicated that the current meteoroid flux in the Earth-Moon system is approximately the same as in the last 100 Myr (Ivanov 2006).

The observed CSFD indicates a flatter slope than the standard size distribution in a diameter range of >80 m (Fig. 3). Such a deflection on CSFD can be associated with a possible resurfacing event (e.g., Neukum and Horn 1976; Hiesinger et al. 2002). However, the standard distribution can fit the CSFD within the uncertainties. Therefore, we do not consider the deflection to be evidence of a possible resurfacing.

We also performed the crater counts on continuous ejecta of three young craters, Byrgius A, Moore F, and Necho, which are summarized in Table 1. The model ages of the craters were estimated to be 48 Ma for Byrgius A, 41 Ma for Moore F, and 80 Ma for Necho. From the new model ages, Giordano Bruno and the three craters are classified as Copernican system, which is consistent with previous geologic maps (e.g., Wilshire 1973; Wilhelms 1987). Furthermore, our results support the classification into a relative age group younger than Tycho crater (Grier et al. 2001).

DISCUSSION

Giordano Bruno has a formation age of 1 to 10 Ma, which we interpret as conclusive evidence against its

Table 1. Model ages of bright rayed craters.

Crater	SEA[a] [*]	Area [km^2]	N(1)[b] [km^{-2}]	Model age [Ma]	Wilshire (1973)	Stuart-Alexander (1978)	Wilhelms (1987)	McEwen et al. (1997)
Giordano Bruno (36°N, 103°E)	34.9	294	3.2×10^{-6}	4				Cc
Byrgius A (25°S, 64°W)	37.0	123	4.0×10^{-5}	48	Cc			
Moore F (37°N, 175°W)	7.1	170	3.5×10^{-5}	41		Ec		Cc
Necho (5°S, 123°E)	9.0	195	6.7×10^{-5}	80			Cc	Cc

[a]Solar elevation angle of image used for crater counting.
[b]Number of craters with a diameter larger than or equal to 1 km per km^2, derived by fitting the standard distribution to observed CSFD.
Cc = Copernican crater. Ec = Eratosthenian crater.

association with the phenomenon in AD 1178. Besides Giordano Bruno, three large craters, Byrgius A, Moore F, and Necho, were classified into the youngest group (Grier et al. 2001). However, these craters are located outside the latitude and/or longitude ranges predicted by the medieval chronicle. In addition, the crater-frequency measurements on the continuous ejecta of these craters give model ages of 10 to 100 Ma, which is ~10 times older than that of Giordano Bruno (Table 1, Fig. 3). Therefore, we conclude that no crater on the Moon is related to the eye-witnessed transient phenomenon in AD 1178.

Other evidence against the recent-formation hypothesis was provided by Withers (2001). He calculated that the formation of Giordano Bruno would cause a week-long meteor storm in the Earth's atmosphere. However, no records of such a storm have been found, implying that Giordano Bruno did not form in 1178. Also, according to the lunar cratering records over the last 3 Gyr (Neukum 1983; Neukum and Ivanov 1994), the average production rate of craters larger than 20 km in diameter on the entire surface of the Moon is estimated to be 0.3×10^{-7} yr^{-1}. This corresponds to 30 Myr intervals of the formations of 20 km-sized craters. Thus, the possibility that the Giordano Bruno-like cratering events occur on scales of several hundred years appears to be small.

Giordano Bruno, which is 10–100 times younger than Tycho, is a key crater for understanding the space weathering process of crater ejecta. It is important to calibrate the ages derived here with parameterized spectral maturity to quantify the recent weathering rate on the Moon. The optical maturity parameter (OMAT), which is calculated from the 950/750 nm ratio and 750 nm reflectance in multispectral data, is an accepted maturity index (Lucey et al. 2000; Grier et al. 2001). There is a good correlation between the ages and the OMAT values of the craters classified into the youngest group; the OMAT values at two crater diameters from the crater centers are estimated to be ~0.27 for Giordano Bruno and 0.22–0.24 for Byrgius A, Moore F, and Necho (Grier et al. 2001), indicating that the Giordano Bruno ejecta (1–10 Ma) is more immature than those of the other craters (10–100 Ma). We will provide a more detailed discussion including analyses of new spectral data (Matsunaga et al. 2008; Ohtake et al. 2008) in future work.

The cratering chronology models that were used in this study represent average cratering rates over long time scales. In the near future, it will be possible to directly measure the present-day flux rate by searching for small, fresh craters. This will provide more solid absolute age estimates especially for young craters like Giordano Bruno.

SUMMARY

New high-resolution images obtained by SELENE/TC show numerous small craters superposed on the ejecta blanket of Giordano Bruno. Based on our crater size-frequency measurements, Giordano Bruno is estimated to have formed 1 to 10 Myr, not 800 years, ago. This is conclusive evidence against its relation to the phenomenon in AD 1178. Considering there is no large crater younger than Giordano Bruno through the global mapping by TC, we conclude that no crater on the Moon is related to the eye-witnessed transient phenomenon in AD 1178.

Acknowledgments—We thank all the contributors to the SELENE (Kaguya) project and Lunar Imager/Spectrometer working group for their efforts in development, operation, and data processing of SELENE and LISM. We are grateful to J. Oberst and an anonymous reviewer for thoughtful and constructive comments in their review of this paper. This work was supported by the Japan Society for the Promotion of Science under a Grant-in-Aid for JSPS Fellows (20·9211: T. Morota), a Grant-in-Aid for Scientific Research (C) (20540416: J. Haruyama), and a Grant-in-Aid for Scientific Research (A) (19204045: H. Demura).

Editorial Handling—Dr. Carlé Pieters

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