Reports

Lunar Crater Giordano Bruno: A.D. 1178 Impact Observations Consistent with Laser Ranging Results

Abstract. *The hypothesis of Hartung, that the impact formation of lunar crater Giordano Bruno (103° east, 36° north) was observed and recorded 800 years ago, is considered in the context of data from the Luna 24 mission and laser range observations. It is concluded that (i) the event would certainly have been visible, and (ii) current determinations of the free libration in longitude in the moon's rotation are consistent with the hypothesis. Such a study cannot prove Hartung's interpretation, but it is nonetheless supportive of it.*

It is a catchphrase of modern astronomy that observers must not be presumed to occupy a privileged position in space or time, despite obvious exceptions in the recent past (comet Kohoutek, Nova Cygni, and so forth). Application of this principle, combined with the observed lunar crater distribution and the observed infall of meteoritic material on the lunar surface, leads one to suppose that the time scale of formation of large craters is measured in millions of years and thus that none should ever have been witnessed by human observers. On the other hand, a recent ($< 10^5$ years) large impact would have left observable dynamical traces in the form of free librations, or Eulerian oscillations, in the rotational motion of the moon. Thus, it was with considerable interest that we read in a newspaper account (*1*) of a hypothesis by Hartung (*2*) that the impact generating the crater Giordano Bruno was observed only 800 years ago.

Hartung's hypothesis, briefly stated, is that the chronicles of Gervase of Canterbury include a striking eyewitness description that may be interpreted as being of the scattering of debris from a major impact on the lunar surface. This was viewed by several "reliable" persons on the evening of 18 June 1178, Julian calendar (JC) (*3*). Apparently, the lunar crescent, which was very thin, was partly obscured by several successive events cutting the horns apart. It is clear that these witnesses were convinced that this remarkable sequence of events was truly of lunar origin. If so, this represents an important event in the recent history of the earth-moon system, and it is of interest to search for physical implications that might provide tests of the hypothesis on the basis of modern observations.

On the basis of the medieval description, Hartung established crude limits on the possible location of the crater resulting from this "impact," and he found a most remarkable one: Giordano Bruno, at 103°E and 36°N. This 20-km-diameter crater shows an extensive and young ray system (see cover), the ratio of ray length to crater diameter being the largest of any lunar crater found (*2*). One of these rays is reported (*4*) to cross the Luna 24 landing site, 1200 km distant.

Hartung's hypothesis must be examined for its dynamical plausibility, which leads in two directions: (i) Would the Bruno impact have been observable? (ii) Would the Bruno impact have left observable perturbations in the present motion of the moon? The first question involves the relation between the locations of the crater, the visible limb of the moon, and the terminator at the time of impact, as well as the trajectories taken by the ejecta as a result of the impact. We shall show that the event should have been easily visible (indeed impressive) to naked-eye observers at Canterbury. As for the second, the moon, like any other physical body, will suffer free oscillations when subjected to impact. The deformational oscillations will be damped to insignificance relatively quickly, but the free oscillations in the rotational motion of the moon, the so-called free librations, have damping times very long compared to 800 years. Thus, their current amplitudes can provide a possible test of the Bruno hypothesis.

Was the event visible? With an east longitude of 103°, Bruno is never visible from the earth. At 2100 U.T., 18 June 1178 (JC), the lunar optical libration in longitude was +1.5°, so the crater was nearly 15° beyond the visible limb. The moon was 1.6 days past new, so the terminator was at east longitude 70°. Thus, the crater was 370 km beyond the limb and 840 km from the terminator along the circle of latitude. The lunar crescent, seen from the earth, subtended a mere 52 arc seconds at the equator and 42 arc seconds at the latitude of crater Giordano Bruno. For the results of the impact to have been noticeable, the ejecta must have attained an elongation comparable to the visible width of the crescent. For the horns to have been completely separated by the cloud of debris, a significant fraction of the ejecta must have passed the terminator.

The visibility is calculated by treating a trajectory of a particle of ejecta as a segment of a selenocentric Keplerian orbit, necessary because the arc length is comparable to the lunar radius. The pertinent parameters are the ejection angle (α), ejection velocity (v), maximum altitude (h) above the surface, and surface distance (d) between the crater and "alunissage" (*5*) of the particle ejected. The specification of any two of these parameters suffices to establish the others, and by extension the visible elongation of the debris cloud (Fig. 1). In our calculations, we have chosen two limiting values for the surface distance d: (i) 500 km because from orbital photography it is easily evident that the ray system extends at least that distance and (ii) 1200 km, the distance of the Luna 24 site. Given the estimation (*6, 7*) that perhaps 1 percent of the ejecta mass would be lost totally from the moon (that is, accelerated to escape velocity, 2.4 km/sec) in such an impact, it is reasonable to suppose that a

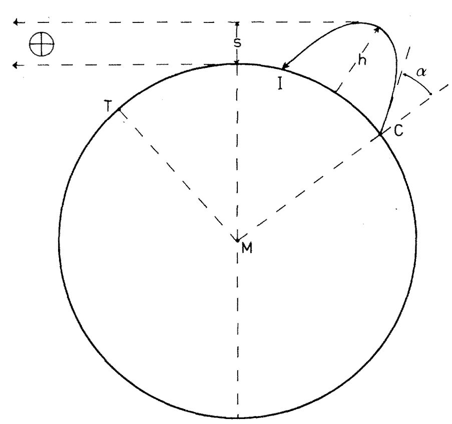

Fig. 1. Geometry of ejecta trajectories and their visibility from the earth (parallel arrows); α is the angle from the vertical at which particles are ejected by the cratering event at C, h the maximum height of the trajectory above the surface, and s the visibility from the earth. The distance d is the arc length along the lunar surface from C to the impact point I. The terminator, represented by T, divides the sunlit crescent from the dark face. The scale is exaggerated for clarity.

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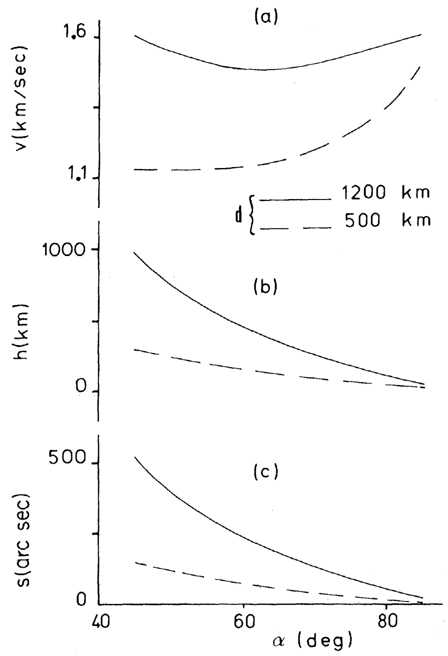

Fig. 2. Ejecta trajectory parameters for surface distances of 500 and 1200 km. (a) Required ejection velocity, (b) maximum height above the lunar surface, and (c) maximum angular extension ("visibility") as seen from the earth.

sizable fraction of the ejecta might fall between these two limits. We have chosen to calculate the conditions for a range of values of ejection angle between 45° and 85° from the vertical; the dynamical solutions do not admit values smaller than 45° for this range of distances (*8*), and Hartung estimates that most ejecta leave around 45°. The results of these calculations are displayed in Fig. 2.

The implications of the curves in Fig. 2 are quite clear. Supposing an impact velocity of $\simeq$ 20 km/sec (see next section), the required ejecta velocities are not unreasonable. For any value of d between the adopted limits, the geocentric elongation of the ejecta is greater than the width of the visible crescent over a wide range of ejection angles, and exceeds it by an impressive factor of 13 in the case of ejecta leaving at 45° and landing 1200 km away. That is to say that the event would have been not only visible but sufficiently apocalyptic to have justified the description given in the Canterbury chronicle. If one supposes a cluster of objects impacting nearly simultaneously, or a quantization of ejection angles, or the impact triggering of volcanism [as proposed by O'Keefe (*9*)], then one might even accept several successive obscurations of the crescent, which is a possible interpretation of the account. The Hartung hypothesis passes the kinematic test of observability.

Free librations. The apparent rotation of the moon is dominated by the spin-orbit resonance that ensures that we always see the same face; that is, the moon rotates once per orbit revolution. Superimposed on this gross motion are periodic variations caused by the gravitational torques exerted by the earth and other bodies on the nonspherical bulges of the moon. Expressions for these variations can be derived from the equations of classical mechanics. There is another mode of oscillation corresponding mathematically to the homogeneous (unforced) solutions of the equations of motion (*10*), or physically to the natural mechanical resonances of the lunar body. These oscillations, or "free librations," are stimulated by impacts on the moon but are gradually damped by internal friction. Their amplitudes at any particular moment are determinable only by measurement, and they are sufficiently small that they can be detected only by the most precise observational techniques presently available—laser ranging and radio interferometry.

The theory for predicting the free librational amplitudes excited by a particular meteorite impact has been derived by Peale (*7*). One of his conclusions is that "the libration in longitude is much more easily excited than the precession." The assumption that there has been no large impact recently (denial of privileged observers) leads him to state further that "amplitudes of this motion as high as 1.0 must be regarded as very unlikely" (*11*). However, an impact 800 years ago would leave residual amplitudes nearly unchanged from their original values, and it is thus of interest to estimate the librational amplitudes that would have been induced by the hypothesized Bruno event. Since these values depend on the (unknown) geometry of the impact, it is necessary to make some plausible assumptions concerning numerical values.

As shown by Peale, the amplitudes are closely specified by the vector components of the angular momentum **L** transmitted to the moon by the impact. One can greatly simplify his expression for the axial and equatorial components (L_a, L_e) of **L**, by introducing the geometric parameters relating the selenocentric crater position and the meteorite velocity vector, as shown in Fig. 3. One obtains

$$L = mvR \sin\sigma$$

$$L_a = L \sin\xi \sin\theta$$

$$L_e = L\,(1 - \sin^2\xi \sin^2\theta)^{1/2}$$

where m is the meteorite mass, v its velocity, and R the lunar radius. Various scaling laws have been derived to estimate impact energy from crater diameter. Adopting as extremes the relations due to Shoemaker *et al.* (*12*) and Gault *et al.* (*13*), combined with the known lunar radius, we obtain

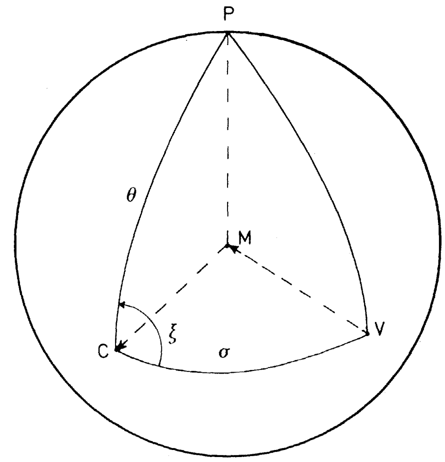

Fig. 3. Definition of geometric parameters of impact energy transfer; *MC* is the selenocentric direction of the crater, *VM* the meteorite velocity direction, and *MP* the lunar rotation axis.

$$1.1 \times 10^{19} < mvR < 2.2 \times 10^{20} \text{ g km}^2\text{/sec}$$

The angle θ is the crater colatitude, 54°. The angle ξ is related to the orbit plane of the meteorite; the fact that it intersected the lunar orbit implies a low inclination, hence we adopt $\sin\xi \simeq +1$. The angle σ is a measure of the impact angle; the circularity of the crater implies $\sigma < 70°$, while the orbital eccentricities commonly associated with comets and meteorites suggest that $\sigma > 45°$; consequently we adopt $\sin\sigma = 0.8$ in our calculations.

There are three modes of free libration. The free libration in longitude is a variation in the rate of rotation about the polar axis, with a period of about 3 years. The amplitude range predicted by Peale's theory applied for the present hypothesis would be

$$0.2 < A_1 < 4.6 \text{ arc seconds}$$

The free precession of the rotation axis in space (period, 27.3 days) would be

$$A_2 < 0.14 \text{ arc second}$$

The third mode is a free precession of the axis of figure relative to the rotation axis (called "wobble" by Peale); its period is 75 years, and the contribution from the Bruno impact is predicted as

$$A_3 < 0.2 \text{ arc second}$$

These values represent the selenocentric displacements. To appreciate them properly, one must recall that 1 arc second selenocentric is equivalent to 8 m at the lunar equator, or an angular displacement of less than 0.005 arc second as seen by an earthbound observer (about 10 percent of the minimum resolution capability of the largest conventional telescopes).

The only observations presently available that are capable of resolving such small displacements of the moon are the series of laser range measures obtained at the McDonald Observatory since the Apollo 11 landing in July 1969 (*14*). We recognized the interest inherent in the possible existence of free librations in 1974, and since that time one of us has undertaken a series of investigations to deduce them from the laser observations (*15*). The techniques required for such a study are too complex to be treated here (*16*), but they have been conducted with several different models of the forced librations and several lunar ephemerides, including those of our own construction. There is considerable inherent difficulty in determining modes A_2 and A_3 with these data; for A_2, the correlations with other parameters having periods close to the sidereal month are enormous, requiring 24 years for good separation; for A_3, the observations cover only 10 percent of a period and thus this parameter can easily be confused with secular variations in other parameters. It appears that the best test of the dynamical consistency rests with the amplitude A_1 of the free libration in longitude; over the past 3 years, with different models, the value given by the laser data has remained essentially constant at about 1.8 arc seconds, which corresponds very closely with the theoretical value for the Bruno event if one adopts an impact energy law midway between the two extremes cited above.

Discussion. Hartung's interpretation of the Canterbury chronicle has been challenged by Nininger and Huss (*17*), who prefer to believe that the event was a meteor entering the earth's atmosphere along the line of sight between Canterbury and the moon. Their claim that the ejecta from a lunar impact would not be visible (citing the naked-eye invisibility of large craters) seems specious since one may imagine a considerably different albedo for a dust cloud than for low-contrast surface features. The reference to the coldness along the ejecta trajectory is also irrelevant. On the other hand, their interpretation requires that the already-improbable trajectory enter the earth's atmosphere at nearly grazing incidence, and atmospheric drag should surely cause a curvature of the path, easily discernible in the line of sight against such a well-defined background object as the 1.6-day-old lunar crescent. Considering that we are dealing with an exceptional event, Hartung's interpretation seems at worst no less believable than that of Nininger and Huss.

From the point of view of the free librations, it is evident that the Bruno impact is very convenient. We have already cited Peale on the values imaginable in the absence of recent stimulation. The results of the laser analyses are only explicable by a recent impact. Thus, as stated by Kovalevsky (*18*), "It could be an interesting challenge to lunar geologists to try to find a very recent crater." Convenience is not an a priori reason for rejection. The laser value of A_1 and the Hartung hypothesis are supportive of one another.

We will be the first to admit that the calculations outlined above do not prove the Hartung hypothesis. What we have done is to show that such an impact would have been observable and that the only modern observations that are capable of revealing the dynamical vestiges of such an event provide a compatible result. Neither the required ejecta trajectories nor the determinations of free librations cited here can be used to refute Hartung's interpretation, which has thus passed a considerable test. Neither can these results be sufficient to confirm it. Perhaps this question can be resolved, or at least narrowed, by the chemical analyses of soil samples returned by Luna 24.

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References and Notes

1. *New York Times*, 26 October 1976.
2. J. B. Hartung, *Meteoritics* **11**, 187 (1976).
3. This is equivalent to 25 June 1178 in the Gregorian calendar. Hartung's paper gives an erroneous Gregorian date, apparently based on the assumption that the difference between the two calendars is constant for all dates prior to the adoption of the Gregorian. There is also a misprint in his first paragraph, giving the month as July.
4. *Sci. News* **110**, 390 (18 and 25 December 1976).
5. We regret that there is no English word to express succinctly "landing on the surface of the moon"; thus, we use the French.
6. J. B. Hartung, private communications.
7. S. J. Peale, *J. Geophys. Res.* **80**, 4939 (1975).
8. For values of the ejection angle smaller than about 45° (the exact value also depends on the other parameters), the implied ejection velocity is sufficient for escape from the lunar gravity field, and the mathematical solution becomes formally imaginary.
9. J. A. O'Keefe, private communication.
10. J. D. Mulholland, *Bull. Sci. Acad. R. Belg.* **60**, 1088 (1974).
11. S. J. Peale, *J. Geophys. Res.* **81**, 1813 (1976).
12. E. M. Schoemaker, R. J. Hackman, R. E. Eggleton, *Adv. Astronaut. Sci.* **8**, 70 (1963).
13. D. E. Gault, J. E. Guest, J. B. Murray, D. Dzurisin, M. C. Malin, *J. Geophys. Res.* **80**, 2444 (1975).
14. There are now available more than 2000 observations of the four reflectors deposited by the Apollo 11, Apollo 14, Apollo 15, and Luna 21 missions. There are as yet no useful observations of the Luna 17 reflector.
15. O. Calame, thesis, University of Paris (1975); *Moon* **15**, 343 (1976); in *Scientific Applications of Lunar Laser Ranging*, J. D. Mulholland, Ed. (Reidel, Dordrecht, Netherlands, 1977), p. 53.
16. ——, *Manuscri. Geodaet.* **1**, 173 (1976); J. D. Mulholland, in *Scientific Applications of Lunar Laser Ranging*, J. D. Mulholland, Ed. (Reidel, Dordrecht, Netherlands, 1977), p. 9.
17. H. H. Nininger and G. I. Huss, *Meteoritics* **12**, 21 (1977).
18. J. Kovalevsky, in *Scientific Applications of Lunar Laser Ranging*, J. D. Mulholland, Ed. (Reidel, Dordrecht, Netherlands, 1977), p. 21.
19. We are very grateful to J. B. Hartung for his cooperation on technical matters, to the Lunar Science Institute for assistance in locating the crater photograph used here, and to the U.S. National Space Science Data Center for providing copies of it for our use. J.D.M. was on partial leave in 1976 and 1977 from the Department of Astronomy and McDonald Observatory, University of Texas, Austin.
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Mid-Recent Human Occupation and Resource Exploitation in the Bismarck Archipelago

Abstract. *Human settlement of the Bismarck Archipelago occurred by 6000 to 7500 years ago. Early inhabitants of New Ireland drew on widely dispersed stone sources, including obsidian from Talasea (New Britain), whereas those after about 3000 years ago used either stone from more local sources or obsidian from Lou Island (Admiralty Islands group) or Talasea. The dates and resource changes support a gradualist model of Melanesian settlement.*

Balof is a small overhang in uplifted corralline limestone, situated about 1 km inland of the east coast of New Ireland and 90 km south of Kavieng (Fig. 1). Six square meters were excavated (*1*); the maximum depth of occupation deposit was 80 cm. There was little visible stratigraphic differentiation, except for recent disturbances in the top 20 cm. Our interpretation is that human treading and scuffing, along with a slow rate of deposit accumulation, has destroyed many formerly visible features. Scattered charcoal fragments found 17 to 23 cm below the surface dated to 1540 ± 270 years ago (GaK 2437: half-life, 5730 years); 550 g of food-bone remains found 58 to 85 cm below the surface dated to ≥ 6800 ± 410 years ago [NSW 95: half-life (corrected), 5730 years]. The dates conform to the hypothesis of steady site accumulation, and the

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