

Climate Change Resulting from Lunar Impact in the Year 1178 AD

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In June of the year 1178, an impact was observed on the Moon. Within a few years, Europe experienced a climatic event known as the Little Ice Age. Calculations of the reduction in sunlight due to dust in high earth orbit are consistent with the historical temperature decrease. Other past temperature reductions may have resulted from similar impacts on the Moon.

1 Historical events

Shortly after sunset on June 25, 1178 AD, a large explosion occurred on the surface of the Moon. This event was observed by several people in Canterbury, England and recorded in the *Chronicles of Gervase*. The Julian calendar date was June 18, or June 25 Gregorian.

In this year on the Sunday before the feast of St John the Baptist, after sunset when the Moon had first become visible, a marvellous phenomenon was witnessed by some five or more men ... and suddenly the upper horn slit in two. From the midpoint of this division a flaming torch sprang up, spewing out over a considerable distance fire, hot coals and sparks. Meanwhile the body of the Moon which was below, writhed, as it were in anxiety... and throbbed like a wounded snake. Afterwards it resumed its proper state. This phenomenon was repeated a dozen times or more, the flames assuming various twisting shapes at random and then returning to normal. Then after these transformations the Moon from horn to horn, that is along its whole length took on a blackish appearance. [4]

2 The crater Giordano Bruno

This event was caused by the impact of a comet or asteroid onto the surface of the Moon, in the approximate area 45 degrees North latitude, 90 degrees East longitude. The crater named Giordano Bruno is believed to have been formed by this impact [6]. Giordano Bruno is a crater which is 20 kilometres in diameter, having unusually sharp rims and an extremely large system of rays. Sharp rims are indicative of recent formation, since micro-meteorites cause erosion which gradually softens land features on the surface of the Moon. Rays, which are believed to be powered material ejected during the crater's formation, do not last very long and are also regarded as evidence of very recent formation. The physical features and location of this crater are consistent with its having been formed by the event of 1178.

3 Energy of crater formation

When an object, such as a comet or asteroid, impacts the surface of the Moon, it penetrates a relatively short distance be-

fore being slowed to sub-sonic velocity. Once this has happened, vaporized material from the impact site expands up and out, forming a fireball and a crater. Factors such as the density of the impactor, the density of the target, and the angle of impact affect the size of the final crater. The most important factor is the total energy of the impacting projectile. In general, calculations involving the crater size will provide only a minimum energy of crater formation. Various formulae have been published which relate the size of a crater to the impact parameters. These formulae show a high sensitivity to the exponent used for the energy, and produce results which rarely have more than one digit of accuracy.

The first method of estimating the energy of formation of the crater is to calculate the energy using a formula which was calibrated with actual data from nuclear bomb tests and multi-ton conventional explosions.

The relationship between crater size and explosion size for an optimal crater forming explosion is the Glasstone formula [5]:

$$\text{Yield} = \left(\frac{\text{Crater Radius at Lip}}{62.5 \text{ meters}} \right)^{3.33}$$

Yield is quoted in kilotons of TNT, which are defined in this context as 4.184×10^{12} Joules. In standard format:

$$D = 2.03 \times 10^{-2} E^{0.3003},$$

where D is crater diameter in meters, E is energy in Joules.

The crater Giordano Bruno has a radius of 10 km, or 10,000 meters. Using the Glasstone formula gives an explosion energy of 21,800,000 kilotons, or $9.1 \times E^{19}$ Joules. This is approximately the energy required to vaporize 21 Gigatons of rock.

A second formula has been published, based on similar data sets, the Dence formula [3]. This formula is for a crater produced by an explosion (sphere or hemisphere) on a flat surface):

$$D = 1.96 \times 10^{-2} E^{0.294},$$

where D is crater diameter in meters, E in energy in Joules.

Using the Dence formula gives 2.74×10^{20} Joules, or 65.5 Gigatons. This is larger than the Glasstone number by a factor of 3, which shows the difference between an optimal depth crater-forming explosion and a surface explosion.

The third method of estimating the energy of formation of the crater relies on laboratory data and computer simulations. The de Pater formula is [2]:

$$D = 1.8\rho_i^{0.11}\rho_t^{-0.33}g_t^{-0.22}(\sin\theta)^{0.333}(2r)^{0.13}E^{0.22}.$$

These parameters are as follows:

| | | |
|------------------|---------------------|---------------------------|
| $D = 20,000$ | crater diameter | meters, |
| $\rho_i = 2$ | density of impactor | gram/cm ³ , |
| $\rho_t = 3.333$ | density of the Moon | gram/cm ³ , |
| $g_t = 1.625$ | gravity of the Moon | meters/sec ² , |
| $\theta = 45$ | impact angle | degrees, |
| $r = 300$ | radius | meters, |
| $v = 28,000$ | velocity of impact | meters/sec, |
| E | energy | Joules. |

This formula requires us to either make an assumption about the velocity of the incoming object, or about its mass (radius). Because of the date of the impact, the object which caused Giordano Bruno is believed to be part of the Taurid meteor complex, which would imply an impact velocity of 28000 meters/sec and a density of 2. Based on these numbers, the radius of the impactor is calculated to be 300 meters, which gives an energy of impact formula of

$$20000 = 1.8 \times 1.08 \times 0.67 \times 0.90 \times 0.89 \times 2.3 \times E^{0.22},$$

which resolves to 6.6×10^{17} Joules (158 Megatons). This is less than 1% of the Glasstone number.

The fourth method is to measure the volume of the crater in cubic meters, estimate the weight of the material which was removed, and estimate how much energy was required to remove the material. The way it works is to model the crater as a hemi-spheroid, then find the mass of the ejecta, and then to calculate the energy required to lift the ejecta to an altitude equal to the crater radius. This method produces a minimalistic number, and is intended as a sanity check on the other methods:

$$\begin{aligned} \text{volume} &= \frac{2}{3}\pi \times \text{radius}^2 \times \text{depth} \\ &= \frac{2}{3}\pi \times 10000^2 \times 1000 \\ &= 2.09 \times 10^{11} && \text{m}^3, \\ \text{mass} &= \text{volume} \times 1000 \times \text{density} \\ &= (2.09 \times 10^{11}) \times 1000 \times 3.333 \\ &= 7.0 \times 10^{14} && \text{kg}, \\ E &= \text{mass} \times g \times \text{altitude} \\ &= (7 \times 10^{14}) \times 1.625 \times 10000 \\ &= 1.1 \times 10^{19} && \text{Joules}, \\ &= 2.7 && \text{Gigatons.} \end{aligned}$$

In standard form, this is:

$$D = 1.9 \times 10^{-1} \times E^{0.25}.$$

Note that this formula produces a number which is proportional to the crater radius to the one-fourth power. This is consistent with the simplest formula published [2].

The four methods of estimating the energy of formation of the crater are as follows:

| | | |
|---------------|----------------------|---------|
| Glasstone | 9.1×10^{19} | Joules, |
| Dence | 2.7×10^{20} | Joules, |
| de Pater | 6.2×10^{17} | Joules, |
| volume method | 1.1×10^{19} | Joules. |

What is interesting is how much effect the exponent in the formula has:

| | |
|---------------|--------------|
| Glasstone | $E^{0.30}$, |
| Dence | $E^{0.29}$, |
| de Pater | $E^{0.22}$, |
| volume method | $E^{0.25}$. |

A relatively small change in the exponent between Glasstone and Dence produced a relatively large change between those two results, and the de Pater result is far away from the others. Given that the Glasstone formula is described as calculating an explosion *at optimal cratering depth*, I suspect that the true number is somewhere between Glasstone and Dence. The best estimate for the energy of crater formation is therefore 1×10^{20} Joules.

4 Historical temperature decrease

Various historical records indicate a global temperature decrease starting in approximately the year 1190 AD [7]. The grape crop in England, which was moderately large in the year 1100, had dwindled to almost nothing by the year 1300. The records of harbour freezing in Reykjavik, Iceland, indicate that the weather became sharply colder around the year 1200. At the same time, the growing season in Greenland became so short that the Viking colonies there were abandoned. Poland and Russia experienced a major famine in the year 1215 AD, which was attributed to the cold weather causing large-scale crop failures:

...in AD 1215, when early frosts destroyed the harvest throughout the district around Novgorod, people ate pine bark and sold their children into slavery for bread, "many common graves were filled with corpses, but they could not bury them all. ...those who remained alive hastened to the sea".

Other bad years came in 1229 and 1230, and in the latter there were many incidents of cannibalism "over the whole district of Russia with the sole exception of Kiev". [8]

Outside of Europe, tree ring data from around the world suggests that the planet became colder starting in the late 1100's [1, 7]. This temperature drop amounted to approximately 1 degree Kelvin.

5 Reduction in sunlight arriving on the planet

These recorded temperature declines are consistent with a reduction in the amount of sunlight arriving on the planet. To reduce the global temperature from 283 to 282 degrees Kelvin using a gray-body model would require that incident radiation be reduced by a factor $1 - (282/283)^4$, or 1.4%. Using a more realistic model which includes positive feedback, only half of the temperature reduction needs to be caused by a decrease in sunlight. With a positive feedback model, we find that radiation needs to be reduced by a factor of $1 - (282.5/283)^4$, which equals 0.7%. Such a temperature reduction would be caused by lunar dust orbiting the Earth.

The most efficient reduction in sunlight per unit mass results from dust particles approximately 1 micron in diameter. Dust particles smaller than this do not absorb light efficiently; they scatter it. Dust particles larger than 1 micron have a reduced surface area relative to their mass, and are less efficient at blocking sunlight.

Given that the required area density of dust particles is 0.7%, we find that 7×10^9 particles are needed per square meter of the Earth's surface. Assuming a dust cloud as high as the Moon, this equals an average particle density of 17.5 particles per cubic meter, or a total of 5.8×10^{26} particles:

$$\begin{aligned} \text{area shadow} &= 0.007/1 \times 10^{-12} \\ &= 7 \times 10^9 \text{ particles/m}^3, \\ \text{density of particles} &= 7 \times 10^9/4 \times 10^8 \\ &= 17.5 \text{ particles/m}^3. \end{aligned}$$

An orbiting dust cloud can be modelled as a solid sphere which contains uniformly distributed particles. The cloud's radius is assumed to be at the altitude of the Moon (400,000 km). The volume is therefore:

$$\text{volume cloud} = \frac{4}{3} \pi (4 \times 10^8)^3 = 2.7 \times 10^{26} \text{ m}^3.$$

Assuming a mass density of 2, each particle would have a mass of 2×10^{-15} kilograms, which gives a mass for the total cloud of 9.5×10^{12} kilograms, or approximately 9.5 Gigatons:

$$\begin{aligned} \text{mass}_{\text{particle}} &= 2 \times (1 \times 10^{-5})^3 = 2 \times 10^{-15} \text{ kg}, \\ \text{mass}_{\text{total}} &= 2 \times 10^{-15} \times 17.5 \times 2.7 \times 10^{26} = 9.5 \times 10^{12} \text{ kg}. \end{aligned}$$

The escape velocity of the Moon is 2373 m/sec, or 2.8×10^6 Joules per kilogram of mass removed from the Moon's gravity well. This gives a total energy required to lift the dust cloud of 2.6×10^{19} Joules, which is less than the calculated energy of the event:

$$E_{\text{orbital}} = 0.5 \times (9.5 \times 10^{12}) \times 2373^2 = 2.6 \times 10^{19} \text{ Joules}.$$

Since not all of the energy went into placing matter into high earth orbit, and since not all of the orbiting matter is in

the form of optimal light-blocking dust, we could expect an efficiency of perhaps 5% in converting the original explosion into an orbiting dust cloud. The indicated efficiency, given that the explosion was 1×10^{20} Joules, is 26%. This suggests that the actual energy of the crater-forming explosion was closer to the Dence number, above.

6 Orbital characteristics of a dust cloud

An orbiting dust cloud such as the one described above would not be stable. Individual particles would experience perturbations in their orbit due to the Moon's gravity, and would also be subject to orbital change due to solar wind, atmospheric drag, and collision with other particles.

In the intermediate term, particles colliding with each other would cause the cloud to assume the shape of a ring. In the long term, the particles would be removed from orbit.

The orbital velocity of the Moon is approximately 1000 meters/sec. For a dust particle moving through the dust cloud described above, the mean distance between collisions would be approximately 1.4×10^{10} meters, which is 1.4×10^7 seconds, or 6 months:

$$\begin{aligned} \text{cross section collision} &= 4 \times (1 \times 10^{-6})^2 \times 17.5 \\ &= 7 \times 10^{-11} \text{ m}^3, \\ \text{mean free path} &= 1/(7 \times 10^{-11}) \\ &= 1.4 \times 10^{10} \text{ m}, \\ \text{mean collision interval} &= \text{mean free path/velocity} \\ &= 1.4 \times 10^{10}/1000 \\ &= 1.4 \times 10^7 \text{ sec}. \end{aligned}$$

How long the cloud would remain in orbit depends on various assumptions regarding its initial orbital characteristics and the level of solar wind activity. An orbital half-life of a few decades seems reasonable.

7 Evidence of Lunar impacts in marine sediments

Much of the mass placed into earth orbit would be recaptured by the Moon, and some would escape to solar orbit, but some large fraction would be deposited on the surface of the Earth. Assuming that some large fraction of the dust eventually was deposited on the surface of the Earth, it should be possible to locate the characteristic Titanium Oxide from the Moon rock in marine sediment or polar ice core samples. If half of the total orbiting dust cloud was deposited on the Earth's surface, there would be approximately 5 grams/square meter. Of this, perhaps 10% (0.5 grams) would be Titanium.

$$\begin{aligned} \text{dust density} &= 50\% \times \text{mass}_{\text{total}}/\text{Earth surface area} \\ &= 0.5 \times (9.5 \times 10^{12})/(4\pi \times (6.3 \times 10^6)^2) \\ &= 0.00475 \text{ kg/m}^2, \end{aligned}$$

$$\begin{aligned} \text{titanium density} &= 0.10 \times \text{dust density} \\ &= 0.000475 \text{ kg/m}^2. \end{aligned}$$

It must also be considered that many of the major ice ages were caused by orbiting dust from the Moon, and that they will also have left traces in the marine sediments. An examination of the sediment samples would show whether the Ice Age which began 15,000 years ago was also caused by an object impacting on the Moon.

8 Objections to this idea

It has been suggested that, after an impact on the Moon similar to the one described in this paper, a large amount of debris would impact the Earth a few days later. It has also been suggested that these impacts would create a spectacular meteor storm, and that the absence of such a meteor storm in the historical record suggests that there was no such impact in the year 1178.

Analysis shows that most of the debris would not create dramatic effects, and that the amount of light emitted by the impacts would be diffuse.

Objects falling from the altitude of the Moon will have an impact velocity approximately equal to the escape velocity of the Earth (11200 meters/sec). The energy released by a 1 micro-gram particle (the size of a grain of sand) impacting at this speed is 62.7 Joules. When this enters the Earth's atmosphere, it will look like a 60-Watt light bulb shining for one second, which is probably not going to create a big psychological impact. Dust particles will produce an even less dramatic effect. Even if 10 Megatons of lunar regolith and dust particles were to hit the Earth in the first month after the impact, it would only add up to 6×10^{14} Joules, or 240 Megawatts. More to the point, this is 4 micro-watts per square meter of the Earth's surface, which is less than 1% of the light from a full Moon.

This amount of light concentrated into a small number of fireballs might be noticed, but spread into billions of individual particles, the energy released would not be spectacular.

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