THE ORIGIN OF THE LUNAR CRATERS.*

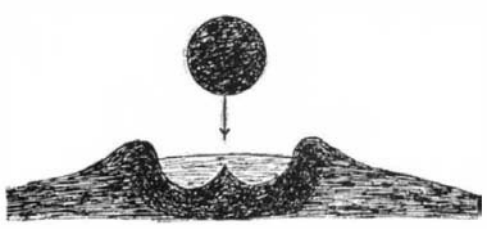
A CONSIDERATION OF THE IMPACT THEORY.

BY T. J. J. SEE.

IN a paper just published in the Astronomische Nachrichten, No. 4367, November, 1909, the writer has treated of the problem of the obliquities of the planets, from the point of view of the capture theory, and has shown that Jupiter's small obliquity has been produced by the capture and absorption by the giant planet of vast quantities of satellites moving about the sun in planes nearly coinciding with the plane of the planet's orbit. It is shown by calculation that if the mass of Saturn were increased by this process of capture till it became equal to that of Jupiter, the obliquity of Saturn would become as small as that of Jupiter; whence it is inferred that Jupiter's obliquity was once large and afterward gradually destroyed by the growth of his mass from the capture of satellites moving near the plane of his orbit. This theory of the planetary obliquities is applied to the other planets of the solar system, and the facts are shown to be in good agreement with the theory.

The origin of the lunar craters has long been a debated question in astronomy, but the traditional opinion dating from the time of Galileo is that they are volcanic; and this view is still held by leading investigators, such as Puiseux, of the Paris Observatory, and Prof. Ebert, of Munich. The theory that the lunar craters are volcanic seems to have originated with Hooke, 1667, and was generally held till the time of Humboldt. About the middle of the nineteenth century, however, several investigators, but especially Humboldt himself, and Schmidt, of Athens, became doubtful of the volcanic origin of these circular mountains, mainly because the inner parts of the craters were found to be depressions, with the central peaks below the average level of the lunar surface. A tentative theory that the craters might be due to impact was outlined by Proctor in 1873, mentioned by Newcomb as a curiosity in 1878, and more fully worked out by the geologist G. K. Gilbert, in 1892; but it has never been accepted either by geologists or astronomers.

After a careful examination of all the evidence, I am satisfied that the impact theory is correct, and that the current volcanic theory is not well founded. It happens that the impact theory brings the phenomena of the lunar surface into harmony with the capture theory of satellites and of the obliquities of the planets; and it will, therefore, contribute to our understanding of the phenomena of the solar system. If Jupiter's small obliquity has been produced by the capture and absorption of satellites, the evidence of such collisions, preserved by the indentations in the moon's face, becomes an important chain in the reasoning for establishing the processes involved in the formation of the planets and satellites. The present discussion is restricted to a brief summary, but the reader who is interested in the subject should be referred to a paper on the cause of the variability of satellites recently communicated by the writer to the Astronomische Nachrichten, and to Gilbert's important paper of 1892. (Bulletin of the Philosophical Society of Washington, vol. xii.)



HOW A LUNAR CRATER IS MADE BY A FALLING SATELLITE.

In connection with the formation of these craters, Capt. A. W. Dodd, U. S. N., has made several valuable suggestions resulting from his large experience in various kinds of target practice. He tells me that when the resisting surface is not too hard, experiments with projectiles indicate that the crater will have about three times the diameter of the impinging shell. Accordingly for the lunar surface, with typical craters about sixty miles across, the impinging satellites probably had a diameter of some twenty miles, about like the planet Eros, or the smaller asteroids.

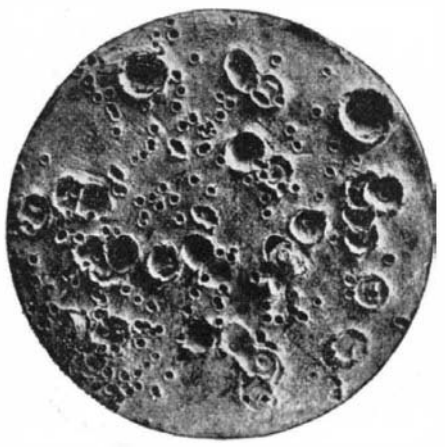
If we wish to calculate the temperature of the falling mass after collision, it is easy to approximate it by the formula for the mechanical equivalent of heat:

$$Q = \tfrac{1}{2}mv^2 = \frac{mv^2}{2 \times 9.81 \times 425} = \frac{mv^2}{8339} \text{ calories.}$$

We find that for a mass of a kilogramme, moving with the parabolic velocity of the lunar surface, 2.37 kilometers per second, the result will be:

$$\frac{[2370]^2}{8339} = 673 \text{ calories.}$$

If the specific heat of a stony satellite be approximately 0.2, as in the case of terrestrial stone, the effect of the total heat of collision would be to raise it to a temperature of 3365 degrees centigrade. But some heat is transferred to the moon's surface and a considerable part of the energy is expended in sinking a crater and throwing up a wall about it. Notwithstanding this division of the energy, it is clear that many of the satellites colliding with the moon would be more or less melted and vaporized. As our moon has no atmosphere, the dust arising from such a conflagration would rapidly fall as metallic and lithic rain, and tend to cover up the ancient craters. The condition of things thus predicted from mechanical theory is strikingly verified by observation of the lunar surface.



INDENTATIONS IN A LEADEN DISK MADE BY BULLETS FIRED BY CAPT. A. W. DODD, U. S. N., AT MARE ISLAND.

It is found that the impact theory explains the following facts:

1. Both large and small craters, and their superposition over one another, some being older and others newer, as the case may be.

2. The frequent occurrence of small craters on the rims of large ones, where they would scarcely arise from eruptive causes.

3. The existence of craters in perfectly smooth plains, as well as in rough and broken regions; and the unequal density of the craters in different parts of the lunar surface. Terrestrial volcanoes generally follow the mountain ranges along the seacoasts. On the moon the craters are scattered indiscriminately, except that they are rare in maria, for reasons which will hereafter appear.

4. The greater steepness of the inner walls, and the great diameters of the larger craters, which could not well be explained by volcanic forces. If it be thought that more larger craters ought to be elliptical than are observed, it may be recalled that, even if the first contact with the moon produced such an outline, the impact of a large satellite would generate enough heat and underlying flow to force out the walls about symmetrically all around, and the final figure would be circular like the globular figure of the satellite. Thus craters which are, say, ten times as wide as they are deep, ought to be almost circular; while smaller craters would be more irregular and elliptical, as found by observation. This is because the forcing out of the material beneath small craters is less effective than in the case of large craters, and they retain more nearly their original shape of first contact.

5. The very flat-bottomed craters, noticed in such regions as Mare Nubium, are due to the filling up of deeper and more irregular craters with cosmical dust, or by melted material, which has assumed a level surface. This has at length become so deep as to leave only the walls visible about a level central area, while the central peaks have been nearly or entirely covered up.

6. In many cases the lunar photographs show that even the walls are practically covered up; for they can now be traced with difficulty, and merely as a faint outline. The walls are covered up, especially in the so-called maria. So far as one can see, two and only two, explanations of these so-called "ghost" craters are possible: 1. The deposit of cosmical dust from the heavens, and from the conflagrations arising in the impact of satellites. 2. The partial melting down of the walls by the conflagrations, which produced the maria, so that only an outline of the original crater walls can be traced. The fact that the "ghost" craters occur chiefly in the level maria supports the conflagration and melting hypothesis, and this certainly is one of the leading causes. But since the earlier craters away from the maria also show the effects of age, as if tending to become obliterated by falling dust, this latter cause also is at work. Moreover, the two causes necessarily are related. Together they explain the ageing of the craters in the rough regions far from the maria, as well as the buried or "ghost" craters in the maria themselves.

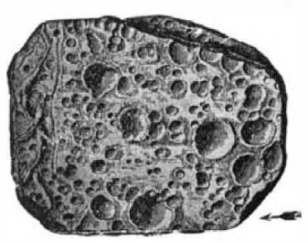
7. This shows that many craters have not only been obscured and partly blotted out by the falling dust, but also that a countless number of these objects have been permanently buried by the process of deposit and conflagration. The so-called seas are areas once made level by melting, in which few recent craters have been formed. The seas of the moon appear to be singularly level, and this can only point to terrible impacts at some time in the past, by which these whole areas were so fused that pretty much all inequalities of level disappeared. They have since been covered with a layer of cosmic dust, but have suffered relatively few large indentations. They generally appear dark, because the surface is nearly level, and the sun's light when reflected is but little scattered and seldom so directed that the beam from any considerable part of the surface passes near the eye of the observer.

8. If this view be correct, it also indicates that the whole moon was formed by accretion, and that the surface never did experience true eruptive phenomena, such as we observe on the earth.

9. The interior of the lunar craters is generally below the level of the surrounding normal surface, and this cannot well be explained except by impact. Volcanic eruptions could not well produce depressions of the crater basins.

"The bottoms of many of the craters are very deeply depressed below the general surface of the moon, the internal depth being often twice or three times the external height." (Herschel, "Outlines of Astronomy," sec. 430.)

This remark of Sir John Herschel's shows that decided depression of the basins is common to all craters, both those with rims and those without. It is almost impossible for volcanic forces to produce such a result. One or two Hawaiian volcanoes are the only depressed craters on the earth, and they are recognized to be exceptions to the general rule of elevation characteristic of our planet.



HOW SOFT MUD IS INDENTED BY FALLING RAINDROPS.

10. It is evident that the craters have not been produced by the removal of material from the center and the piling of it up to make the surrounding walls; for in probably three-fourths of the cases, as Prof. H. Ebert has shown, it is easily proved by calculation that the volume of the excavation exceeds the volume of the material contained in the wall. This remarkable volume relationship would be explained if the matter beneath the crater were compressed by the force of impact, and only a part of it and of the falling satellite forced out to form the surrounding walls.

11. The shorter streaks radiating from such centers as Copernicus and Aristarchus are easily explained. It is sufficient to suppose that the collision was so forceful that matter was scattered far out in all directions, and perhaps heated to fusion in the process; yet, as the moon has no oxygen, it did not burn and blacken as meteoric stones do in falling on

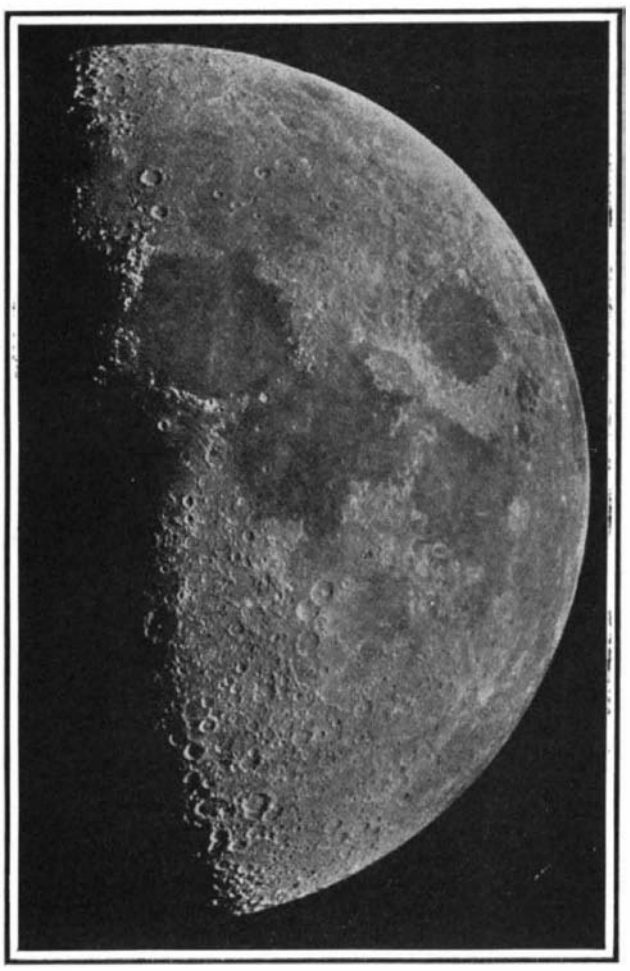
* Presented to the Astronomical Society of the Pacific, November 25th 1909.

the earth, but simply took on a fused and glassy aspect, which, by reflection, gives the brightness of the shorter streaks radiating from Tycho and its associates. This explanation was given by Mr. Würdemann, of Washington, D. C., many years ago, in a letter to Dr. B. A. Gould, but it seems to be but little known to astronomers.

12. The long rays from craters such as Tycho are similar optical effects of glassy material falling on walls of craters lying nearly in a straight line, and radiating from this center. This is shown by the photographs. Any crater which had matter ejected from it radially, in the process of formation, will have a system of rays, due to the effect of the sunlight on the higher elements of the surface traversed by the rays running from the crater as a center.

13. As the moon's force of gravity is feeble, the vapor and metallic and lithic rain due to impact might be carried hundreds of miles, and these streaks due to material falling on corrugations and ridges might extend out from the craters for a considerable distance, and sometimes appear to be prolonged by coincidence with other crater walls or ridges.

14. The craters, which are simple depressions without sensible walls, are to be explained by the comparative looseness of the material of the moon's surface layers, which allows the mass to yield downward without throwing up much of a wall about the depression produced.



THE MOON SEVEN DAYS OLD, SHOWING THE GREAT NUMBER OF CRATERS DOTTING THE SURFACE OF THE SATELLITE.

Photographed by Ritchie at Yerkes Observatory.

MARE SERENITATIS, MARE TRANQUILITATIS AND SURROUNDINGS, SHOWING GHOST CRATERS BURIED BY CONFLAGRATION AND DEPOSIT.

Photograph by Ritchie at Yerkes Observatory.

15. The clefts are paths cut by glancing satellites, which thus leave a straight or curved line, according to the nature of the surface and the resistance and rebound. Photographs confirm this origin of the clefts, and show that they are not cracks, but actual cuts, sometimes more than a hundred miles in length.

16. Rills are cracks or offsets along walls of craters which often are more or less hidden by later deposits. They pursue in some cases an irregular course, and often may be due to settlement of loose material, as in landslides on the earth.

17. Changes in the aspects of a crater due to caving in, settlement, etc., are always possible; but to be entirely certain that the change is real, the illumination has to be exactly the same at the two epochs, which is seldom possible. If the suspected changes are real, photography will eventually establish this fact.

18. The covering up of ancient cities on the earth is due to deposits of waste, rubbish and dust traceable to meteorological causes connected with the atmosphere, such as sand borne by the wind from the desert, etc. On the moon, however, there is no atmosphere sufficiently dense to carry dust, and it must, therefore, be scattered by impacts and by direct descent from celestial space. The fact that the older craters are visibly covered up, is a tangible proof of the part played by cosmical dust in the course of ages.

19. The different degrees of obliteration shown by the various lunar craters is an impressive witness to the progressive falling of cosmical dust, in a celestial world devoid of rain or other meteorological disturbance of any kind.

20. At zero degree centigrade the maximum molecular velocities of the atmospheric gases are found by Dr. Johnstone Stoney to be as follows: Oxygen, 1.8 miles; nitrogen, 2.0; water vapor, 2.5; helium, 5.2; hydrogen, 7.4. These values usually decrease with the fall of temperature, but the modification thus arising is not very considerable for small changes.

21. Now, at the surface of the moon, the parabolic velocity is 1.5 miles (2.41 kilometers, cf. A. N. 3992, p. 136), and, therefore, none of these atmospheric gases can be retained. For, although we do not know the moon's temperature very accurately, it would seem that during the lunar night, it must approach the absolute zero, while during the day it cannot well exceed the boiling-point of water. Accordingly, the above values are not sensibly altered by the admissible variations of temperature.

22. Observations on the refractions of stars occultated by the moon prove that if any sensible atmosphere exists at the lunar surface, it does not exceed 1-5000th part of the density of the terrestrial atmosphere. We may, therefore, conclude that no sensible atmosphere has ever existed upon the moon, either before or since the capture by the earth; but that the vapors there arising have congealed into dust or constantly escaped into space.

23. The cosmical dust that falls upon the moon, therefore encounters no atmospheric resistance, but plunges headlong against the lunar surface. Any vapor due to the force of collision quickly cools and is, if it condenses into solid particles, precipitated as dust, and nowhere amounts to a permanent cloud. If it remains true gas, the molecules gradually escape into space.

24. If now we compare the lunar photographs with the accompanying imprints made by raindrops, and by bullets fired into a leaden disk as a target, we shall notice the most remarkable similarity in the two effects. The raindrops, however, are all fluid, and leave only saucer-shaped imprints, and no central peaks; whereas the leaden bullets and stony satellites indenting the lunar surface would necessarily leave central peaks, in accordance with observations. Thus the moon's surface can be nothing but fragments of rock filled with finer dust; and it is evident that it has never been molten as a whole and has never shown true volcanic activity, as known upon the earth.

The last conclusion is confirmed from another point of view by an exact calculation given in A. N. 4053, p. 345, showing that the total gravitational heat of condensation of the matter of the moon would raise an equal mass of water through only 408 degrees centigrade. It is there pointed out (p. 348) that the development of such a small amount of heat, in the course of long ages, would not at any time give rise to a temperature that would produce fusion of rock. Even when radio-active substances are considered, the conclusion is the same—namely, that in the slow and almost insensible development of the moon by accretion, enough heat to produce general fusion could not have arisen.

Accordingly we may dismiss the old volcanic theory once for all as false and misleading; and may look upon our satellite as a battered planet, which presents to us the most lasting and convincing evidence of the processes of capture and accretion by which the heavenly bodies are formed.

The strength of the present argument regarding the origin of the lunar craters does not rest on one class of phenomena alone, but on several distinct classes of phenomena, which are all harmonized among themselves and brought into accord with the necessary processes of planetary growth. Since worlds form in nebulæ, it follows that impacts will necessarily occur and the moon's face shows the size of these masses by their imprints, which thus throw an unexpected light upon the state of the solar system in the past.

The variability of the satellites of Jupiter and Saturn, photometrically investigated by Guthnick in A. N. 4023 and A. N. 4098, indicates that they, too, have maria covering their surfaces, due to collisions, as in the case of the moon. For, as observed from a distance, the moon also would be variable, according to the extent of the maria on the side toward the sun. Lastly, the mathematical argument regarding the capture of the satellites and the moon is confirmed by Schroeter's observations, 1789-1793, showing that the planet Venus rotates in 23 hours 21 minutes. For, if Venus has that period, the earth never could have rotated faster than at present, and the moon necessarily would be a captured planet. There is found also to be a theoretical reason why Venus ought to rotate faster than the earth, so that the capture of the moon is confirmed both by the observations of Venus and by mathematical theory, and the origin of the lunar craters by impact is a necessary corollary to the capture theory of satellites.

U. S. Naval Observatory, Mare Island, Cal.

In a patent recently issued to Dr. C. P. Steinmetz, a description is given of a machine having interpoles without winding which operates sparklessly. The armature of the machine is of the closed-coil type provided with both a commutator and collector rings. The arrangement for operation is such that the m.m.f. of the current entering by way of the collector rings is greater than that leaving by way of the commutator, and the excess m.m.f. serves for exciting the interpoles to the extent required for sparkless operation. This result is obtained when the machine receives all of its power over the collector rings, and delivers only a part over the commutator, the remainder being utilized mechanically at the pulley.