ORIGIN OF THE MOON BY TIDAL CAPTURE
AND SOME GEOPHYSICAL CONSEQUENCES

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(Received 15 December, 1971)

Abstract. Of the many proposed modes of origin of the Moon, some violate physical laws; many are in conflict with observations; all are improbable. Perhaps the least improbable – based on recent tidal theory calculations and on the interpretation of lunar rock data – is capture of the Moon as it passed near the Earth in a direct (prograde) orbit, shortly after the formation of Moon and Earth, about 4.5 billion years ago. (Capture of the Moon from an initially retrograde orbit which had been proposed some years ago, leads to physically unacceptable consequences.) The effects of capture on the Earth would have been cataclysmic, leading to intensive heating of its interior, to volcanism, and to the immediate formation of an atmosphere and hydrosphere. Thus capture of a Moon may have given rise to the unique properties of the Earth (in the Solar System) and to the early evolution of life, about 3.5 billion years ago.

Various authors have postulated a formation of the Earth-Moon system which involves a capture of the Moon. This process was first proposed by Gerstenkorn in Germany in 1955. He started with the present orbit of the Moon and calculated its orbit in prehistoric times by considering the effects of the Earth's tides on the lunar orbit. He found that the Moon's orbit would shrink from its present near-circular orbit of 60 R_E distance to a much smaller orbit, approximately 2½ R_E, and then would suddenly be transformed into an escape orbit which moves away from the Earth to infinite distances. Taking this result at face value, Gerstenkorn assumed that the Moon approached the Earth about 2 billion years ago along a retrograde hyperbolic orbit, i.e., moving in a direction opposite to that of the Earth's spin, and was captured by the effects of the Earth's tides. In the process, the orbit was flipped over the Earth's pole and changed into a direct or prograde orbit corresponding to the present sense of motion of the Moon.

After Gerstenkorn, Alfvén developed some further details of capture. However, it was shown by MacDonald and more recently by Wise that during the process of capture the energy dissipated in the Earth's interior would become so large that the Earth would evaporate. Other objections were also developed but the energy dissipation became the major one.

What I want to tell you here today is that the objections raised against capture apply only to the so-called retrograde capture calculated by Gerstenkorn and expanded in more detail by MacDonald. If the Moon could be captured from a direct orbit, then the difficulties would disappear. About two years ago, I showed that this kind of

* Presented at the NATO Advanced Study Institute on Lunar Studies in Patras, Greece, September, 1971.
direct capture of the Moon could follow naturally, provided one used a physically more correct version of the tidal theory, namely a frequency-dependent tide whose dissipation angle and phase depends on the relative angular velocity of Moon and Earth.

In this initial work I had taken the Moon to move in the equatorial orbit of the Earth and I had neglected solar torques and many other refinements. For this reason, the result was not generally accepted. I have now had an opportunity to extend this work into three dimensions, taking into account eccentricity as well as inclination of the lunar orbit, the effect of the Sun, the higher harmonics of the tidal potential, the effects of the formation of an Earth core, various ranges of assumptions on the elasticities of the Earth and Moon, and other refinements. But, most important, I have been able to extend the frequency-dependent tidal theory into three dimensions. But the result of all this work has been to recover essentially the same basic results that I had before. In a way, of course, this is very satisfactory.

I will now summarize these results and their consequences for the Earth and Moon, and I will then compare this tidal capture of the Moon from a direct orbit with other capture theories, as well as with other theories of the origin of the Moon, such as fission from the Earth and accumulation of the Moon from small particles in Earth orbit. I will not discuss the latter two modes of origin in any detail because Goldreich in a classic paper has shown that these modes of origin are not compatible with the presently observed orbit of the Moon.

First, then, I want to state my conclusions. My recent three-dimensional calculations, using the frequency dependent tidal theory, taken in combination with data from the Apollo 11 lunar rocks, reaffirm my earlier results and make it most likely that the Moon was captured by tidal forces from a direct orbit. Such a capture would have taken place more than 4 billion years ago, would have caused melting in the Earth's interior, produced volcanism, and given rise to an atmosphere and hydrosphere.

As you can see, therefore, I link the capture of the Moon, which is a fairly rare and rather improbable event, with the equally rare type of occurrences on the Earth; namely, the formation of an ocean, unique in the solar system; the development of life and of the oxygen-rich atmosphere. Presumably, therefore, if the Moon had not been captured by tidal effects early in the Earth's history, then we would not be here to discuss these events.

My picture of the early history of the Earth-Moon system is as follows. The Moon was formed as a sister planet of the Earth about 4.6 billion years ago but in an orbit which is very similar to that of the Earth, that is, at the same distance from the Sun and roughly the same eccentricity and inclination. As a result of these similarities of orbit, the Moon would come close to the Earth every few years and, from time to time, it would come quite close. The most likely thing to happen is exactly - nothing. The Moon simply passes by the Earth and leaves again, but is free to try the same thing over after a few years. The next most likely thing to happen, interestingly enough, is for the Moon to crash into the Earth and thereby disappear. The least likely thing to happen - improbable but not impossible - is for the Moon to be captured.

I cannot prove this, of course, but I would speculate that there may have been