AN ALTERNATIVE HYPOTHESIS FOR THE FORMATION OF THE MOON. R. J. de Meijer[1] and W. van Westrenen[2], [1] Stichting EARTH, de Weehorst, 9321 XS Peize, The Netherlands (rmeijer@geoneutrino.nl), [2]VU University Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands (wim.van.westrenen@falw.vu.nl).

Introduction: The giant impact hypothesis [1,2] is the cornerstone of current lunar formation research. However, recent analyses of the elemental and isotopic composition of lunar samples show degrees of similarity between Moon and Bulk Silicate Earth (BSE) that are inconsistent with hydrodynamic models of the Moon-forming giant impact showing 60-90% of the Moon is made up of impactor rather than terrestrial material [3].

At present, this inconsistency is dealt with by invoking full post-collisional elemental and isotopic equilibration between Earth and proto-Moon as proposed for oxygen by [4] for elements from H to W. In essence, the giant impact hypothesis currently relies on the applicability of a equilibration scenario that is untested for elements other than oxygen.

Here we propose an alternative explanation for the compositional correspondence between Moon and BSE, namely that the Moon was formed from the ejection of terrestrial mantle material in a heat-propelled jet, triggered by a run-away natural georeactor at Earth's core-mantle boundary (CMB). Our hypothesis straightforwardly explains the identical isotopic composition of bulk silicate Earth and Moon for many elements withour relying on full post-collisional equilibration.

Background: High-precision measurements of the oxygen [5], potassium [6], neodymium [7] and tungsten [8] isotopic composition of lunar rocks show that the bulk silicate Earth (BSE, i.e. mantle + crust) and the inferred bulk lunar composition show a very high degree of similarity. Even the water content of the interior of the Moon could be as high as that of Earth's mantle[9].

These results are very difficult to reconcile with the giant-impactor hypothesis for the formation of the Moon. High-resolution smooth-particle hydrodynamic simulations of this impact indicate that 60-90% of the Moon would originate from the impactor, with only 10-40% originating in the Earth. Models of solar system evolution show that it is highly unlikely for the chemical and isotopic composition of the Earth and impactor to be identical (e.g. [4] and references therein). The Moon therefore either consists almost entirely of material originating in Earth's mantle, or complete isotopic homogenisation of terrestrial and lunar material must have occurred after the impact. Although homogenisation in a turbulent exchange between the partially molten and vapourised Earth and Moon system shortly after the impact may be able to explain the similarity in oxygen isotopes [4], it is improbable that such a mechanism would work equally well for much heavier, refractory elements including Nd, Hf and W.

A simpler explanation for the large degree of compositional similarity between the BSE and Moon is that the Moon derives directly from terrestrial material. In one of the first lunar formation hypotheses by Darwin [10], the Moon indeed originated from a hot, fast-spinning Earth. In Darwin's model, the proto-Earth is a rapidly rotating body with gravitational forces at the Earth's surface only barely exceeding centrifugal forces. A slight increase in angular velocity would allow part of Earth's equatorial mass to be ejected into space. Calculations in the 1950s showed that the required increase in angular velocity is inconsistent with the angular momentum of the Earth-Moon system – the Earth lacked sufficient energy to eject our Moon. As a result, this so-called 'fission' hypothesis was abandoned before the Apollo missions.

We have re-examined the energetics of initial Earth-Moon separation and quantified the missing energy term. We show that this missing energy could be supplied by a supercritical georeactor in Earth's core-mantle boundary (CMB) [11], producing sufficient heat to vaporize and eject part of the silicate earth.

Quantification of Missing Energy Term: We consider the Earth and Moon as a gravitationally bound two-body system, where in the groundstate, just prior to separation, the Moon is part of the Earth. In the excited state, just after separation, the Moon circles the Earth at a distance r_{EM}.

Defining the binding energy of the two bodies as the sum of their internal energies, E_b, and denoting the rotational motion of the two bodies by their moments of inertia, I, and rotational frequency, ω, we may write for the total energy, E_{tot}, of the two body system:

$$E_{tot} = E_b + \frac{1}{2}(I_M \omega_M^2 + I_E \omega_E^2 - \gamma \frac{m_M m_E}{r_{EM}}). \quad (1)$$

The total angular momentum of the system, L, is according to Steiner's theorem given by:

$$L = I_M \omega_M + I_E \omega_E + m_M r_{EM} v. \quad (2)$$

In our model we move from a groundstate in which the system is a single body with mass m_E:

$$E'_{tot} = E_b + \frac{1}{2} I'_E (\omega'_E)^2, \quad L = I'_E \omega'_E, \qquad (3)$$

to a two-body state with energy and angular momentum given by equations 1 and 2. In the transition we assumee that total angular momentum is conserved. The energy difference follows from the energy expressions in equations 1 and 3. The radius of the lunar orbit and the energy required for the transition are coupled since angular momentum conservation is imposed.

Using the angular momentum of the present Earth-Moon system ($3.5*10^{34}$ kg m^2 s^{-1} with an equatorial tilt of 9.7°) and assuming the shape of the proto-Earth to be an oblate ellipsoidal with a longer axis twice as long as the shorter axes, the sum of the rotational and gravitational energy totals $2.87*10^{30}$ J for the Earth-Moon groundstate. This value is an order of magnitude smaller than the binding energy, confirming that the original Darwin hypothesis is energetically unfeasible.

For the excited state, shortly after separation, the gravitational energy depends on the distance between the Moon and Earth. A value of r_{EM} around 10^8 m is reasonable if angular momentum is conserved, resulting in the energy required to launch the Moon of $0.5*10^{30}$ J. The corresponding velocity of the proto-Moon becomes $1.9*10^3$ m/s (Eqn 1), corresponding to a rotation period of 9.2 h around the proto-Earth and an angular momentum carried by the proto-Moon of 1.3 kg.m^2.s^{-1} (40% of the total angular momentum of the Earth-Moon system). Immediately after separation, the rotation period of the proto-Earth decreases to 5.7 h. Due to tidal forces energy and angular momentum are transferred from the Earth to the Moon until they have the present properties.

Source for Missing Energy- Nuclear Excitation: We recently assessed the feasibility of georeactors in Earth's CMB [11]. We showed that selective incorporation of U, Th and Pu by the silicate mineral calcium silicate perovskite (CaPv) in the CMB leads to a concentration of fissionable material which is only a factor of twenty lower than required for igniting and maintaining a nuclear breeder reactor, even if U, Th, Pu and CaPv are assumed to be distributed homogeneously throughout the CMB.

Seismic observations show that the CMB is far from homogeneous even today, making a concentration factor of twenty not unreasonable. We concluded that natural georeactors in the CMB are feasible, especially in the earliest stages of Earth evolution. Here we discuss the consequences of one of these reactors becoming supercritical, and providing the missing energy to eject the Moon.

The required size of a run-away reactor can be estimated if the assumption is made that the required excitation energy of $0.5*10^{30}$J is supplied by nuclear fission. This requires fission of $6.1*10^{15}$ kg of a natural U+Th mixture to separate the Moon from the Earth at t= -4.5 Ga, corresponding to 1% of the fissionable U+Th in the BSE (or 5% of a 'hidden' CMB reservoir [7]).

Ejecting the Moon: The heat produced by the run-away reactor is assumed to be produced faster than its dissipation by conduction or convection. The resulting heat is sufficient to raise the temperature of one lunar mass by approximately 8000 K. As a consequence, the run-away georeactor and its surrounding material vaporise. Due to negative buoyancy the vaporized material moves towards the surface, gains potential energy and launches overlying material into orbit.

Testing the Hypothesis: The dominant supporting evidence for our hypothesis is the correspondence in isotopic and elemental composition between the BSE and (surface) lunar rocks. Positive identification of nuclear fission products from the georeactor in lunar material would strongly support our hypothesis. Isotopic compositions of noble gases helium and xenon are particularly sensitive to the presence of fission products [11]. The magnitude of these changes depends critically on the proportion of supercritical georeactor material that is eventually ejected, a parameter that is poorly constrained. Hydrodynamic models of the dynamics of run-away deep georeactors should be constructed. Finally, the presence of georeactors in the deep Earth can be tested by directional geoneutrino tomography (e.g. [12].

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