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Preface

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The origin of the Moon

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The Moon has been an issue of deep fascination for centuries, particularly for the Royal Society. Modern astronomy can be said to have started with Galileo's observations of the Moon and the surprise discovery that it was not smooth, as was assumed based on the then accepted concept of perfect spheres in the heavens. Instead it was found to have irregular features on its surface, rather like the Earth. This year (2014) scientists are celebrating the 400th birthday of John Wilkins, who became Warden of Wadham College, Oxford, UK (<http://www.wadham.ox.ac.uk/news/2014/july/celebrating-science>). He was an intellectual of some breadth but was particularly impressed with Galileo's images and discoveries, and, together with Robert Hooke, worked on the idea of travelling to the Moon and the design of a space craft to achieve this [1]. So far as we know the space craft was never constructed but Wilkins did bring scientists together to discuss this and other issues at Wadham and this led directly to the founding of the Royal Society, the world's first scientific academy, in 1660.

Today, decades since Apollo, lunar science is at a truly interesting stage of development. There are two key sources of information for elucidating the origin of the Moon, the data for which have become significantly more comprehensive in recent years. The first is new dynamic modelling, which is not just based on more powerful computational codes but also on a challenging exploration of the uncertainty surrounding some fundamental accretion parameters. The second is measurement of the isotopic composition of particular elements in lunar and terrestrial samples at unprecedented precision.

These two approaches have provided powerful constraints that pose a series of tests to the current paradigm of the Giant Impact model of lunar formation. Key observables about the Moon that need to be explained with this or any model are as follows:

- (1) It has a lower density than the Earth.

- (2) It is larger relative to the size of its planetary host than any other moon in the Solar System.
- (3) It is moving away from the Earth and was previously much closer.
- (4) It carries most of the angular momentum in the Earth–Moon system.
- (5) It formed very late (more than 30 Ma after the start of the Solar System)—far later than predicted for planetary embryos of this size.
- (6) There is evidence that it had a fiery start with a global magma ocean leaving distinctive trace element features in magmas that remelted the resulting cumulate pile.
- (7) It is depleted in moderately volatile elements relative to the Earth.
- (8) Every non-volatile element analysed so far has an almost identical isotopic composition to that in the Earth, even for elements for which meteorites from elsewhere in the Solar System are different.

The late stage collision of the proto-Earth with another planet often called Theia provides the ‘least worst’ explanation for many of these features. This Giant Impact model has been developed over the years from the early ideas of Reginald Daly [2], to the more comprehensive multiple collision version of Hartman & Davis [3] and the angular momentum argument of Cameron & Ward [4]. In the 1980s, the powerful smoothed particle hydrodynamic simulations of giant impacts were developed by Benz *et al.* [5], and these were followed by more detailed modelling by Canup (reviewed in [6]). In all these computer simulations, the angular momentum (4 above) is generated by the impact itself, Theia striking Earth with a glancing blow. In these simulations, the material forming the Moon is mostly derived from Theia. This feature of successful Giant Impact simulations has been the hardest to reconcile with geochemical data. The fact that the isotopic compositions of silicate Earth and Moon are *so* similar despite evidence that other objects are different provides evidence that either:

- (1) The innermost Solar System from which these two objects formed was not so heterogeneous after all or Theia accreted at a similar heliocentric distance to the Earth [7,8].

or

- (2) The atoms of the Moon were derived from the Earth after core formation and the ‘traditional’ simulations are incorrect [9–11]. New dynamic models have been proposed in which the angular momentum constraint is violated (i.e. the Earth–Moon system began with over twice its current angular momentum) and the excess is extracted by a resonance involving the Sun [10].

or

- (3) There was isotopic equilibration between the atoms in the lunar accretion disc and those in the Earth’s magma ocean [12].

Determining which of these models is correct is crucial to understanding, not just the formation of the Moon itself, but also the conditions under which terrestrial planets more generally accreted. Each of these suggested resolutions has its difficulties. The first is not readily reconciled with the current accretion models. The second relies on a resonance that may only work for a narrow range of tidal parameters and the third relies on an unlikely high efficiency of mixing (in particular, between the interior of the Earth and the moon-forming disc).

In understanding the Moon’s origin and early development, a number of other issues need to be addressed.

First, we do not know the composition of the Moon very well. The GRAIL mission has opened up the opportunity to explore this in detail.

Second, the age of the Moon is poorly defined. It is clearly late (more than 30 Ma) but how late is less certain. The oldest lunar rocks have been redated with more precise modern methods and show no sign of antiquity before about 4.35 Ga—about 200 Ma after the start of the Solar System.

Third, we do not have a clear idea of the manner in which the Moon first developed. It was thought to be a fiery start with a lunar magma ocean, but some of the features of the ages and chemistry of lunar anorthosites might be better explained by more localized magmatism.

Fourth, there is considerable uncertainty about how the Moon became so depleted in volatile elements. Some of this may have arisen from the Giant Impact itself, but it is also possible that early lunar volcanism led to losses.

Last, there is debate about what has happened to the Earth and Moon since the Giant Impact—how did the Moon affect Earth's early evolution and to what extent do the differences in volatiles reflect late additions to the Earth since that time.

These and other aspects are discussed in the following papers from the Royal Society's 2013 meeting on The Origin of the Moon. It was a lively meeting held in London and then the Kavli Centre in Chicheley Hall. The discussion was intense. Sadly, one of the contributors to that meeting, Prof. Colin Pillinger CBE FRS, subsequently passed away. He began his scientific career studying lunar volatiles and was still working on new ESA missions to the Moon for sampling the regolith and understanding surface water reservoirs when he died. In between he had led the Beagle 2 mission to Mars to search for signs of life, among many other contributions. One question that recurred during discussion at the Royal Society conference on 'The Origin of the Moon' was that of what single piece of information the speakers would want to know to move the science forward. A recurring answer was the composition of Venus. It would tell us if the Earth and Moon are unusual in being so similar isotopically. The main meetings around the origin of the Moon have been held in 1984 (Hawaii), 1998 (Monterey) and 2013 (London). On this basis, the next meeting might be in 2027 or so. Hopefully, we will have made progress towards studying Venus by that point in time. I am sure that Colin Pillinger would have been keen to be involved.

References

1. Chapman A. 1991 A world in a Moon; John Wilkins and his voyage of 1640. *Q. J. R. Astron. Soc.* **32**, 121–132.
2. Daly RA. 1946 Origin of the Moon and its topography. *Proc. Am. Phil. Soc.* **90**, 104–119.
3. Hartmann WK, Davis DR. 1975 Satellite-sized planetesimals and lunar origin. *Icarus* **24**, 504–515. (doi:10.1016/0019-1035(75)90070-6)
4. Cameron AGW, Ward WR. 1976 The origin of the Moon. *Abstr. Lunar Planet. Sci. Conf.* **7**, 120–122.
5. Benz W, Slattery WL, Cameron AGW. 1986 Origin of the Moon and the single-impact hypothesis I. *Icarus* **66**, 515–535. (doi:10.1016/0019-1035(86)90088-6)
6. Canup RM. 2004 Simulations of a late lunar-forming impact. *Icarus* **168**, 433–456. (doi:10.1016/j.icarus.2003.09.028)
7. Wiechert U, Halliday AN, Lee D-C, Snyder GA, Taylor LA, Rumble DA. 2001 Oxygen isotopes and the Moon-forming giant impact. *Science* **294**, 345–348. (doi:10.1126/science.1063037)
8. Herwartz D, Pack A, Friedrichs B, Bischoff A. 2014 Identification of the giant impactor Theia in lunar rocks. *Science* **344**, 1146–1150. (doi:10.1126/science.1251117)
9. Zhang J, Dauphas N, Davis AM, Leya I, Fedkin A. 2012 The proto-Earth as a significant source of lunar material. *Nat. Geosci.* **5**, 251–255. (doi:10.1038/ngeo1429)
10. Ćuk M, Stewart ST. 2012 Making the Moon from a fast-spinning Earth: a giant impact followed by resonant despinning. *Science* **338**, 1047–1052. (doi:10.1126/science.1225542)
11. Canup RM. 2012 Forming a Moon with an Earth-like composition via a giant impact. *Science* **338**, 1052–1055. (doi:10.1126/science.1226073)
12. Pahlevan K, Stevenson DJ. 2007 Equilibration in the aftermath of the lunar-forming giant impact. *Earth Planet. Sci. Lett.* **262**, 438–449. (doi:10.1016/j.epsl.2007.07.055)