Earth Sciences in the 21st Century: Submission from the Royal Astronomical Society (RAS)

The Royal Astronomical Society (RAS), founded in 1820, encourages and promotes the study of astronomy, solar-system science, geophysics and closely related branches of science. The Society represents around 3400 members (Fellows), a third based overseas, who include scientific researchers in universities, observatories and laboratories as well as historians of astronomy and others. As such, we are pleased to contribute to this consultation.

In our submission, we wish to draw attention to the issue of the interaction between the Earth and its wider space environment, without which the terrestrial system cannot be properly understood. Further, we also draw the attention of the final authors to the need for studies of the Earth to be supported by a better understanding of the other planets in the Solar System.

A separate response will be sent in from the British Geophysical Association (BGA), the joint committee of the RAS and the Geological Society which represents the solid Earth geophysics community.

Interaction of space phenomena with the Earth

The existing consultation document rightly identifies the need to understand the Earth as a system – how our environment is determined by the interplay of oceans, atmosphere, core, continents and life. However, this view omits one important factor – namely how space phenomena interact with the Earth. There is growing evidence that we should not consider the Earth as a system isolated from its context in the Solar System and the wider Universe. This is noted in parts of the existing documents: e.g. where it highlights the role of the geomagnetic field in protecting Earth's atmosphere from erosion by the solar wind. However, there are many other phenomena that should be considered including:

- The role of energetic particle precipitation (e.g. from solar energetic particle events) in generating significant quantities of nitrogen oxides (NOx) in the middle atmosphere. This has the potential to affect ion chemistry in the middle atmosphere, and at lower levels as the extra NOx is transported downwards.
- Cosmic rays are the major source of ionisation in the upper troposphere (> 3000m altitude). Thus changes in cosmic ray fluxes such as those induced by solar activity and changes in interstellar space have the potential to influence atmospheric ion chemistry.
- Cosmic rays are also of interest as a potential mechanism to trigger lightning. Cosmic ray showers intersecting thunderclouds will deposit substantial fluxes of relativistic electrons which will provide a seed population that can readily trigger lightning discharges in the electric fields (with strengths of $\sim 10^5$ V m^{-1}) observed in such clouds.
- Ablation of micro-meteoroids deposits significant quantities of iron as micro-particles in the upper atmosphere. The upper atmosphere wind systems transport these to the polar regions, where they are thought to descend to sea level and form a major source of the iron needed by plankton at the base of the ocean food chain.

- Electric currents in the ionosphere and magnetosphere can couple to the crust via magnetic induction and thereby generate significant electric fields in the crust. Where surface conductivity is low, these fields can generate currents in man-made conductive structures such as power grids, signal control circuits and pipelines. These geomagnetically induced currents are one of the many natural hazards now emerging within the field of space weather.

This list is not meant to be complete. Rather we seek to demonstrate the general case that “space” should be considered an important factor in Earth System Science alongside other factors such as oceans and atmospheres. The development of Earth System Science must be open to space phenomena such as those listed here plus others that will doubtless emerge as our understanding develops.

We note that there are already two major foci for the effects of space phenomena on Earth. One is to better understand the contribution of solar activity to climate change. The historical record suggests that solar activity was the major driver for climate change prior to the onset of major anthropogenic forcing (greenhouse gases and aerosols) in the twentieth century. However, the physical mechanisms by which solar activity can affect climate are still a major research topic – progress here is essential to reduce the high risks and uncertainties associated with climate change.

The other major focus is space weather – the wide range of space phenomena that can disrupt advanced technologies of economic and societal importance. We touched on one aspect (geomagnetically induced currents) above, but many others can also reach down into the surface environment on Earth.

We also note that the coupling between Space and Earth is not a one way process. There is abundant evidence for how environments in near-Earth space are affected by processes originating on Earth. Examples include:

- The geomagnetic field. The internal field of our planet extends far into space where it interacts with the supersonic flow of plasma from the Sun to form the magnetosphere.

- The free oxygen in Earth’s atmosphere is a major influence on the near-Earth space environment. As a result Earth’s upper atmosphere is dominated by atomic oxygen rather than carbon dioxide as at Mars and Venus. This has major practical impacts for many space applications.

- The recent discovery that the equatorial ionosphere is modulated by tidal modes originating in the lower atmosphere. This has highlighted the growing interest in the modulation of the ionosphere by processes originating in the lower atmosphere, e.g. tidal modes and acoustic gravity waves. There is much interest in this area as it has the potential to explain many aspects of ionospheric variability that have so far defied explanation.

Planetary and lunar science

The Earth is a planet, and as such cannot be properly understood without reference to the other planets of the Solar System. Planetary science, and especially comparative planetology, provides insights into understanding the Earth, just as studies of the Earth provide insights into the understanding of other planets. Indeed, as our knowledge of other planetary environments has become more mature, the links between planetary science and the other geological sciences have become stronger. Many key areas of expertise developed in the context of terrestrial geoscience (including, but not limited to, sedimentology, igneous petrology, structural geology, and geophysics) are routinely used to understand the evolutionary histories of the other terrestrial planets. In the future and certainly well within the 21st century, it is very likely that other areas of terrestrial geoscience capabilities and expertise (e.g. exploration geophysics and sub-surface drilling) will be applied to the exploration of other planetary bodies in the Solar System.

Conversely, studies of the interactions between interiors and atmospheres of bodies such as Venus, Mars and Titan help inform understanding of similar processes on Earth (and thus 'Earth System Science') by enabling studies of the effects of key variables (e.g. gravity, insolation and atmospheric pressure and composition) which cannot be varied experimentally. In addition, studies of the early history of the Earth, which comprise one of the key initiatives identified in this consultation (Initiative 4: Origins) cannot be divorced from the early evolution of the Earth-Moon system, which gives lunar science a particularly important supporting role in studies of the early Earth.

For these reasons, we believe that any strategy for the Earth Sciences in the 21st century must allow for, and further develop, interaction with the planetary sciences. We wish to address one specific area in more detail, namely that of lunar science and the early history of the Earth.

Initiative 4 of this consultation addresses the subject of "Origins: how did the atmosphere, oceans, continents, core and life itself originate?" The origin of the Earth cannot be seen in isolation from the origin of the rest of the Solar System, which implies a strong link with planetary science (and indeed the wider astronomical sciences). In particular the origin, and early history, of the Earth cannot be separated from the origin and early evolution of the Earth-Moon system. Initiative 4 recognizes the importance of "the Moon-forming impact and its aftermath'. Similarly, it identifies a key question to be "What was the nature of the Hadean (>4 billion years old) environment?", but identifies few specific research objectives intended to address these issues.

The truth is that the Earth itself no longer retains any record of these early events (and hardly any of the first 1 billion years of its history). On the other hand, the immediate consequences of the Moon-forming impact (assuming for the moment that this paradigm of Moon-formation is correct, which is not certain), and the subsequent history of the newly formed Earth-Moon system, are well preserved on (and within) the Moon. In particular, the Moon apparently still retains its original crust (which the Earth has long lost), formed by the crystallisation of a magma-ocean immediately following the giant impact. Similarly, the structure of the lunar mantle (and core if present) likely retains a record of the structure of a newly differentiated terrestrial planet (without the corrupting influence of billions of years of mantle convection, as in the case of the Earth's mantle). Thus a better understanding of the Moon's internal structure, formation and early history cannot fail to inform a better understanding of the earliest events in Earth's history.

Moreover, the relatively accessible lunar surface retains a record of the inner Solar System environment, and thus the Earth's environment, over the last 4.5 billion years of Solar System history. This includes a complete record of the meteoritic bombardment rate (and its variation through time [1]), a record of solar wind implanted in the lunar regolith (and thus variations in solar activity throughout Solar System history [2]), a similar record of galactic cosmic rays (and thus a record of high energy galactic events which may have influenced the Earth's environment), and a possible record of the Earth's atmospheric composition through time (likewise implanted in regolith particles [3]). It is even possible that the lunar surface has collected fragments of the Earth's earliest crust, blasted off the surface of our planet prior to 3.8 billion years ago [4].

For all these reasons, lunar science has much to tell us about the history, and especially the earliest history (i.e. the first billion years) of our own planet. While lunar science (and planetary science more generally) is and will be mostly supported by STFC (and the newly formed UK Space Agency), strengthening links with the terrestrial geosciences (mostly supported by NERC) will greatly benefit both communities, and should be part of a 21st century strategy for the Earth sciences.

Summary

We believe that any twenty-first century view of the Earth Sciences must set the Earth in its context in the Solar System. It is important to consider the physical processes that enable space phenomena to couple with those occurring in the Earth's atmosphere, oceans and crust.

Finally we note that the current BBC series "Wonders of the Solar System" provides a popular exposition of this approach. A key aim of the programme is to demonstrate how the same laws of physics apply across the solar system but produce the wonderful diversity revealed by the exploration of our own planet and of other worlds.

References

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[4] Armstrong, J.C., Wells, L.E. and Gonzales, G., (2002). Rummaging through the Earth's attic for remains of ancient life. Icarus 160, 183-196.