WHY IS THE MOON GREY?*

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The solar wind continuously bombards the sunlit side of the Moon with hydrogen atoms or the equivalent thereof contained in a neutral plasma. The protons, together with their equally numerous electrons, arrive at a velocity of some 300 km s or 450 eV of kinetic energy. Electrons, by leaping out from lunar surface so to speak, will neutralize the incoming protons. It is essentially a hot hydrogen atom that impinges on the lunar minerals. Hydrogen atoms, in the energy range of several hundred electron volts, constitute a very powerful reducing agent, able to reduce any known material.

Thus we have a situation in which the Moon is being continually reduced to lower valence states. One could well ask why the surface is not covered, to a considerable extent, with bare metal. The answer is fairly obvious, in that the amount of hydrogen produced over the span of time, generally thought to be some 4.5 billion years, is not adequate to totally dominate the chemical situation. For instance, with some five protons per cc, traveling at 300 km s, the flux is some 10^8 hydrogen atoms or more accurately 0.75×10^8 hydrogen atoms per square centimeter of sunlit surface, which averaging with the dark side gives 0.4. This over a period of 4.5×10^9 yr amounts to 0.8 of a meter of water, that is the hydrogen contained in 0.8 of a meter of water if spread uniformly over the lunar surface.

The back reaction, the reaction which prevents the Moon from being totally reduced, is the photodissociation of water by solar ultraviolet light. Water molecules, so dissociated into the hydrogen atom and the hydroxyl radical, will most of the time lose the hydrogen atom from the Moon and leave the hydroxyl radical, which will in turn either oxidize the surface rocks or will be further photolyzed to give atomic hydrogen and oxygen. The oxygen will certainly oxidize the rocks on contact. Thus we have a titration, or a balance achieved between the reduction tendencies of the solar wind and the oxidation tendencies of the solar ultraviolet acting on water vapor.

Since we see that the Moon is grey, we can conclude that the total oxygen released by photodissociation of water vapor in the whole history of the Moon should not have exceeded that equivalent to 0.8 of a meter of liquid water. This is an interesting result, for many scientists have expected that the Moon would have more water. Of course, the validity of the result may be questioned, for we have no definite assurance that the

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solar wind has remained at its present intensity throughout planetary history. It is, however, an additional control and observable to be used in analysis of the situation.

Mars, obviously being red, has turned a corner in that it has evolved more water than the solar wind equivalent. It is perhaps well at this point to point out that the specific chemical which accounts for the red color is the mineral hematite, Fe_2O_3, the trivalent oxide of iron. The reduced oxide of iron, FeO, and its combination with hematite, Fe_3O_4, lodestone, are both dark. Only the fully oxidized trivalent iron oxide is red. No other minerals are present in adequate abundance to account for planetary color.

The far greater abundance of surface water on Earth, some 2800 m equivalent depth on the average, as compared to less than one meter on the Moon if our assumptions are correct, would seem to indicate that there has been much less surface water on the Moon. There is a mechanism for destroying water and causing it to leave, which is dominant in the lunar situation. As remarked some time ago [W. F. Libby, *Science* **166** (1969), 1437–1438], the escape time of water molecules from the lunar surface is most likely to be slower than the photodissociation process. Over the great reaches of geological time, this would most definitely have left the Moon in a red colored condition if more than a meter of water was exuded, or the solar wind has not remained at its present intensity. There is of course, the possibility that red beds may exist on the Moon which have been buried. However, there has been no evidence for the red mineral, hematite, in any of the lunar samples. It seems clear, therefore, that the average intensity of the solar wind must have been some forty or fifty times greater than the present intensity or else the Moon has released much less water than the Earth. With 1.2% of the mass of the Earth, if the water were proportional, the Moon should have produced thirty-four meters equivalent. About all we can really say is that the superficial water on the Moon is some forty times less abundant than that on the Earth, or the solar wind has averaged some forty times its present intensity.

The input of solar hydrogen to the Earth is minimal because the Earth's magnetic field deflects the solar wind and it does not contact the Earth's surface. Water vapor, on the other hand, could proceed uninhibited to accumulate from the beginning of terrestrial history with partial photolysis to make hydrogen which would escape as a neutral atom and build up the oxygen atmosphere.

If we turn to the other planets, the question of the state of oxidation of Venus is a fascinating one. The solar wind does have access to its atmosphere, since there is no magnetic field on Venus; but if Venus has the moisture content of the Earth, the atmosphere is undoubtedly, nevertheless, oxidizing. This is confirmed by the abundance of carbon dioxide as compared to methane. Therefore, were we able to see the surface of Venus, we would expect it to be brilliantly colored with ferric oxide. On Jupiter, however, the situation is quite different, in that the reducing nature of the atmosphere is very well established and the well known color of Jupiter is most likely due to different phenomenology: namely, organic compounds produced by ionizing radiation. Probably organic dyes are as good a candidate as any other. The peculiar behaviour of the red spot remains a mystery, but it is possible to reproduce the color of the red spot by the use of ionizing radiation on a gaseous mixture simulating the supposed composition of the Jupiter atmosphere (private communication from Cyril Ponnamperuma).

In summary, we see that the color of the planetary surfaces can be a useful indicator of the geochemical history of the planets and their atmospheres. We see that a magnetic field can promote the oxidation of an atmosphere by keeping the solar wind deflected. We see that the amount of water naturally exuded from the planetary interior is an important parameter in determining whether the surface becomes oxidizing or remains in the reduced condition in which presumably all planetary surfaces began.

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